

Imaging the proton with long-range correlations at the LHC

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North Carolina State University



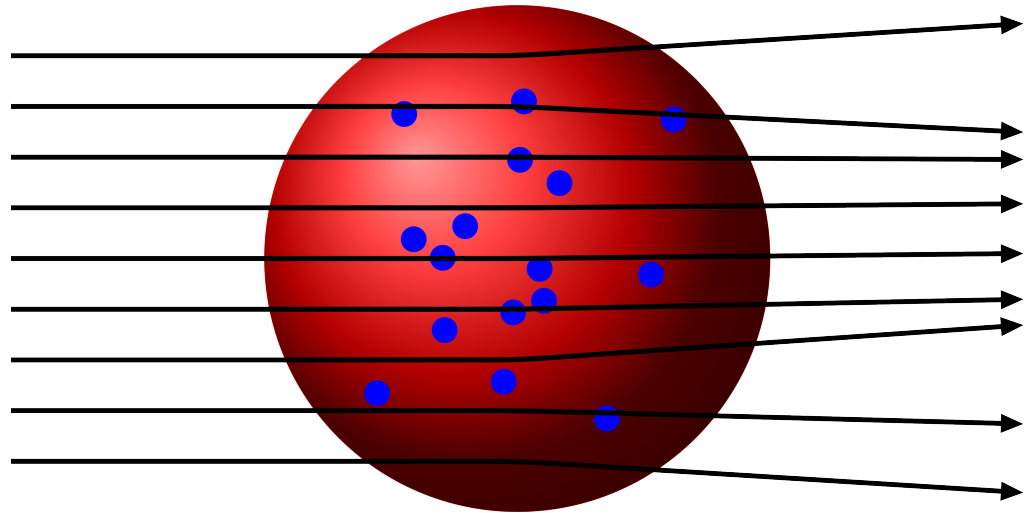
January 15th, 2013

Structure of the atom

Joseph Thompson discovers electron in 1897:
"corpuscles" of charge 1000 times smaller than the atom itself

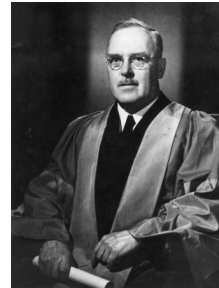
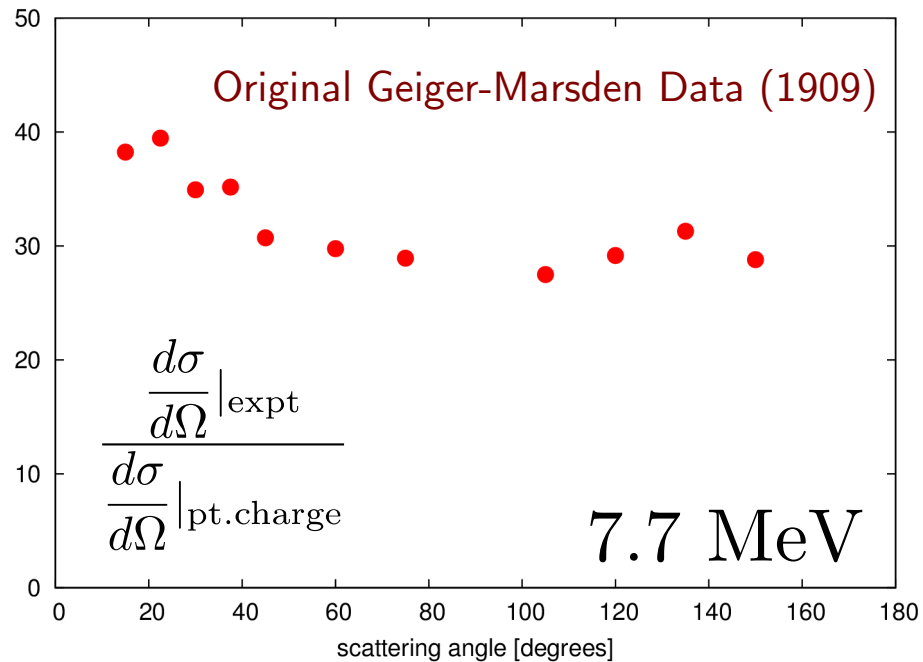


1906 Nobel Prize in Physics



"... the atoms of the elements consist of a number of negatively electrified corpuscles enclosed in a sphere of uniform positive electrification ..." (1904)

Rutherford Scattering (1911)



Marsden



Geiger



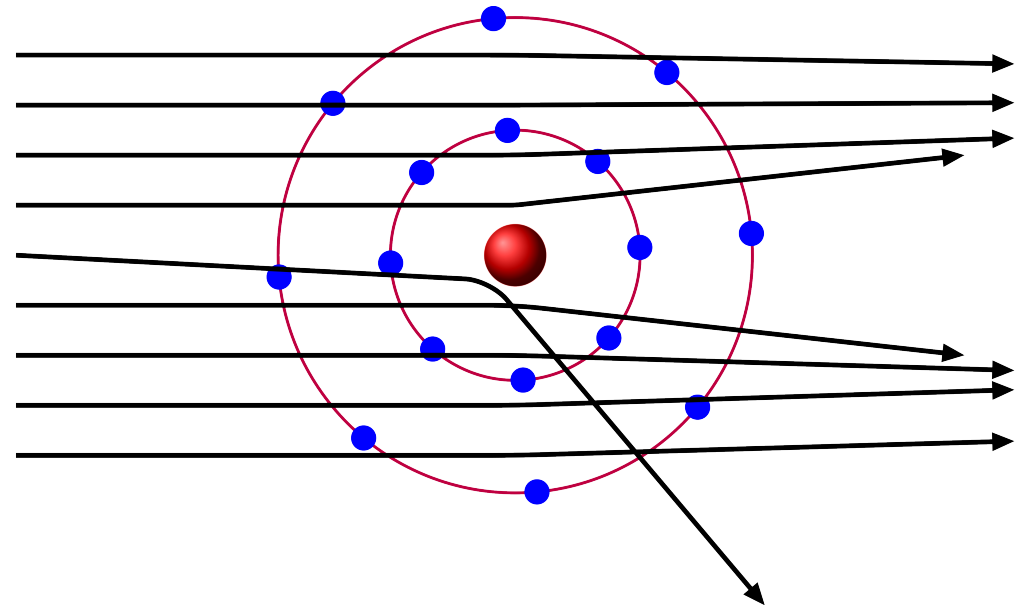
Geiger

Rutherford

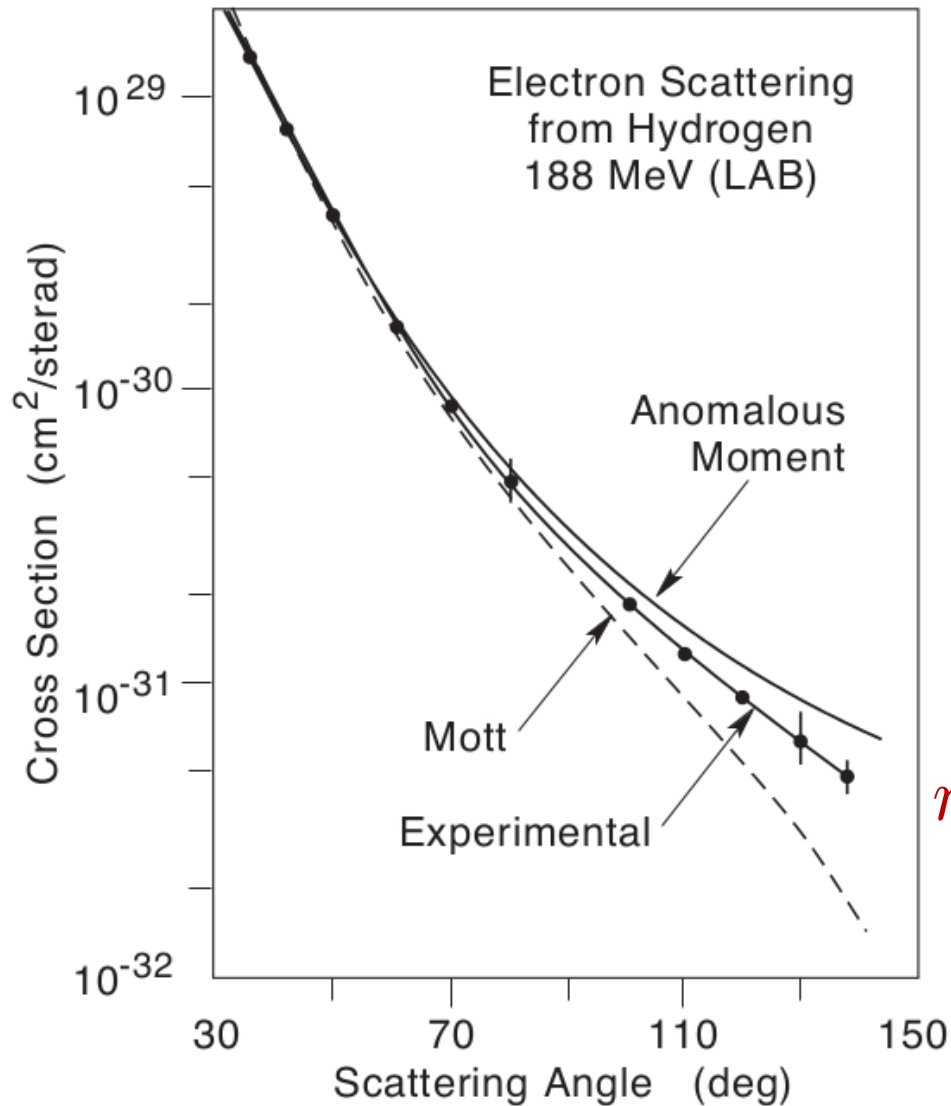


Rutherford
Nobel Prize in Chemistry 1908

$$r_{\text{gold}} \lesssim 27 \times 10^{-15} \text{ m} \\ = 27 \text{ fm}$$



Electron Scattering (1955)



$$r_{\text{proton}} \approx 0.7 \text{ fm}$$



Robert Hofstadter
1961 Nobel Prize in Physics

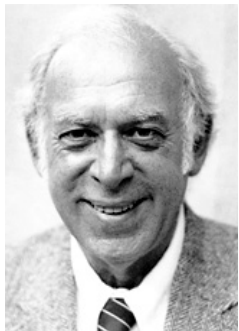
The proton is not a point particle; it has a finite size!

What resides in the proton?

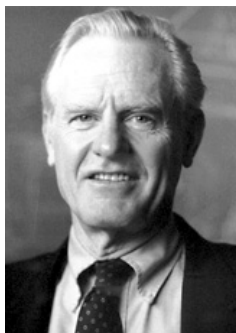


1968: J.D. Bjorken predicts that if high-energy photons resolve point-like constituents then:

$$\nu W_2 (\nu, Q^2) \rightarrow F_2 (x)$$



Friedman

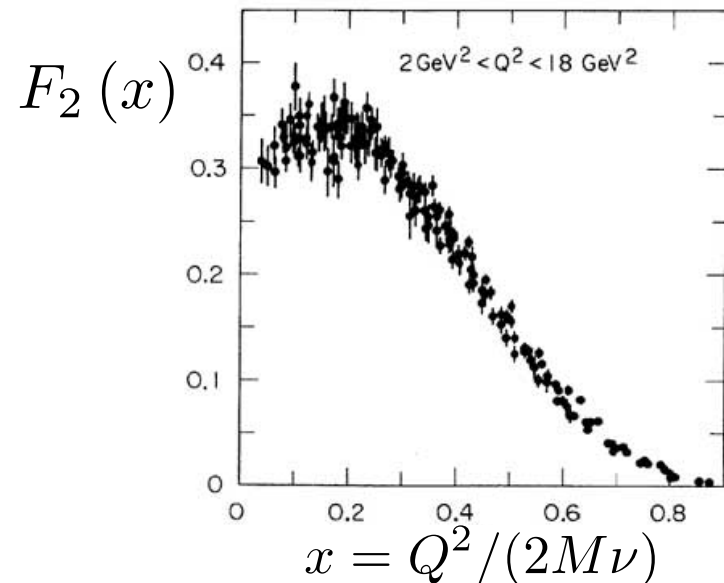
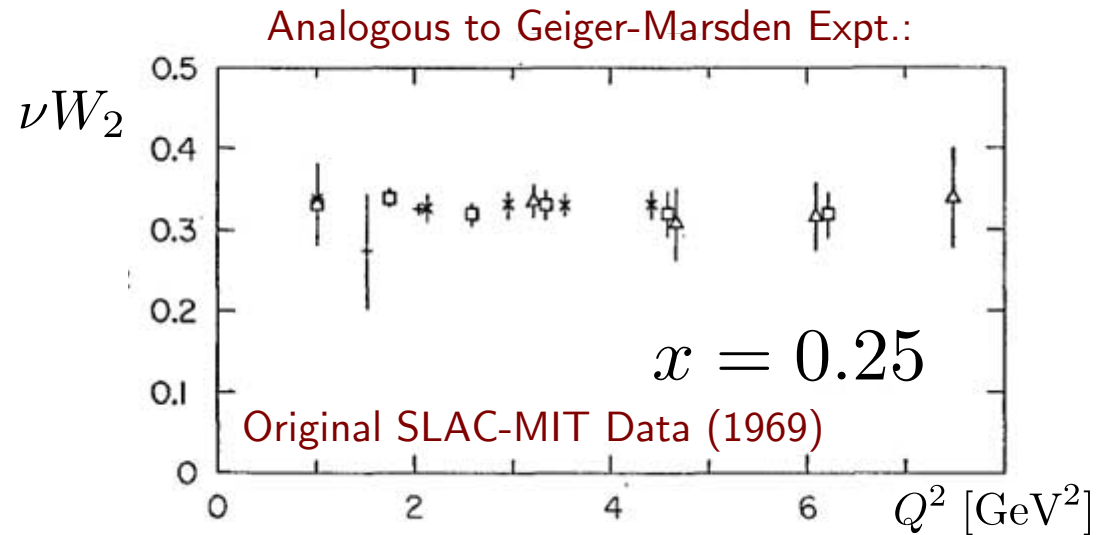


Kendall



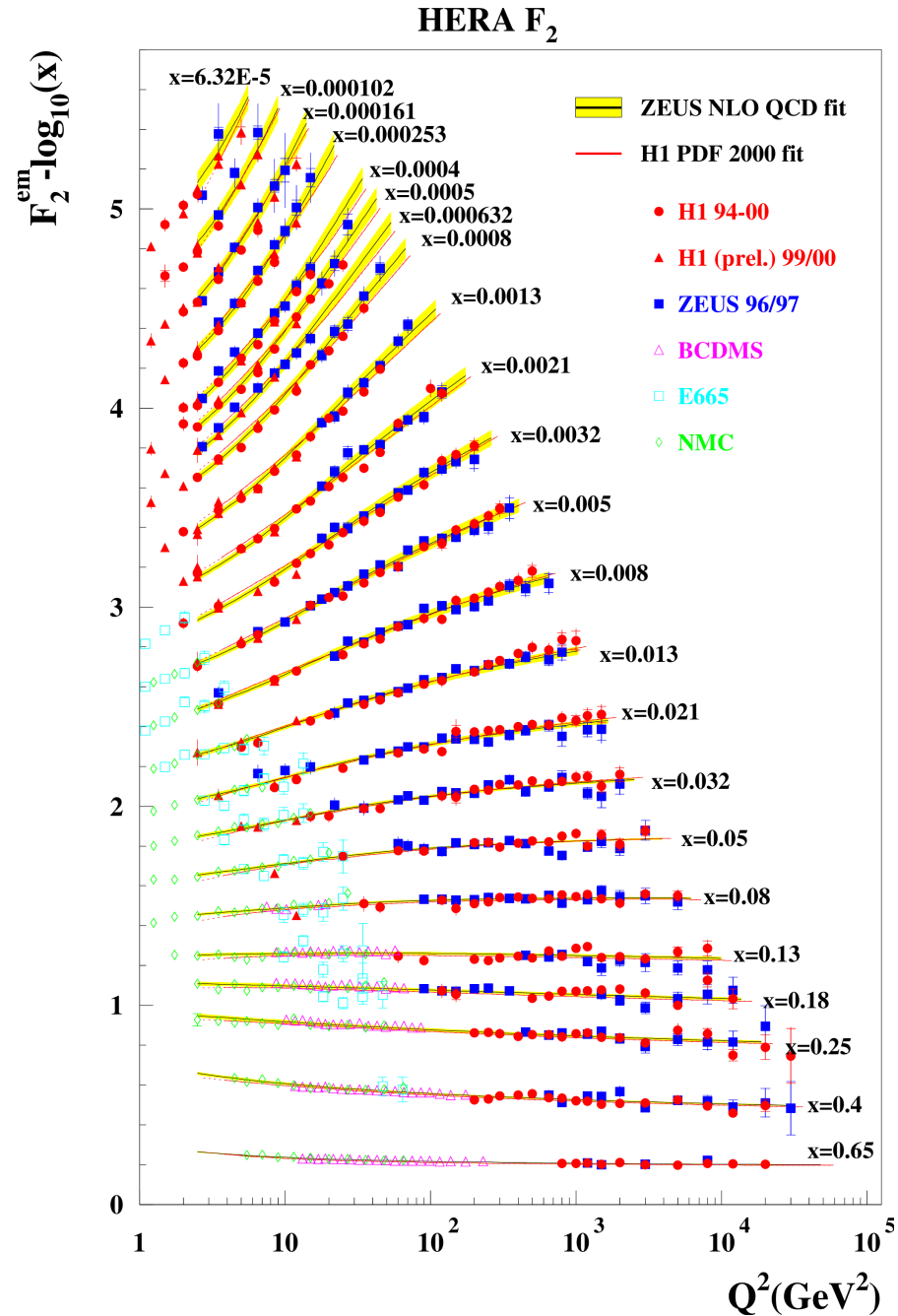
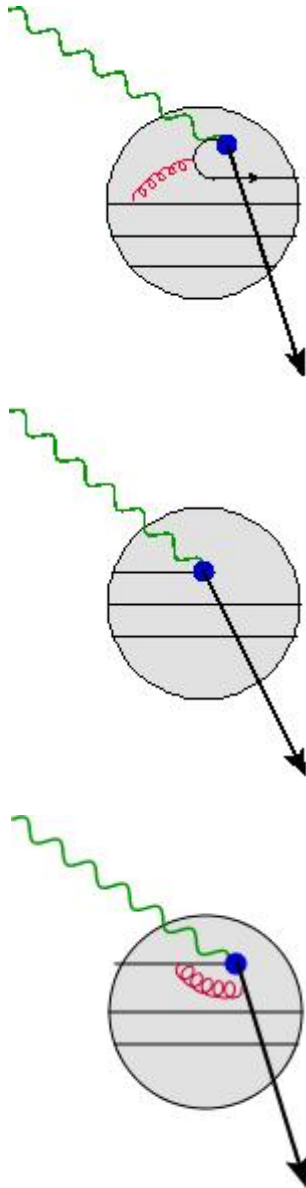
Taylor

Nobel Prize in Physics 1990

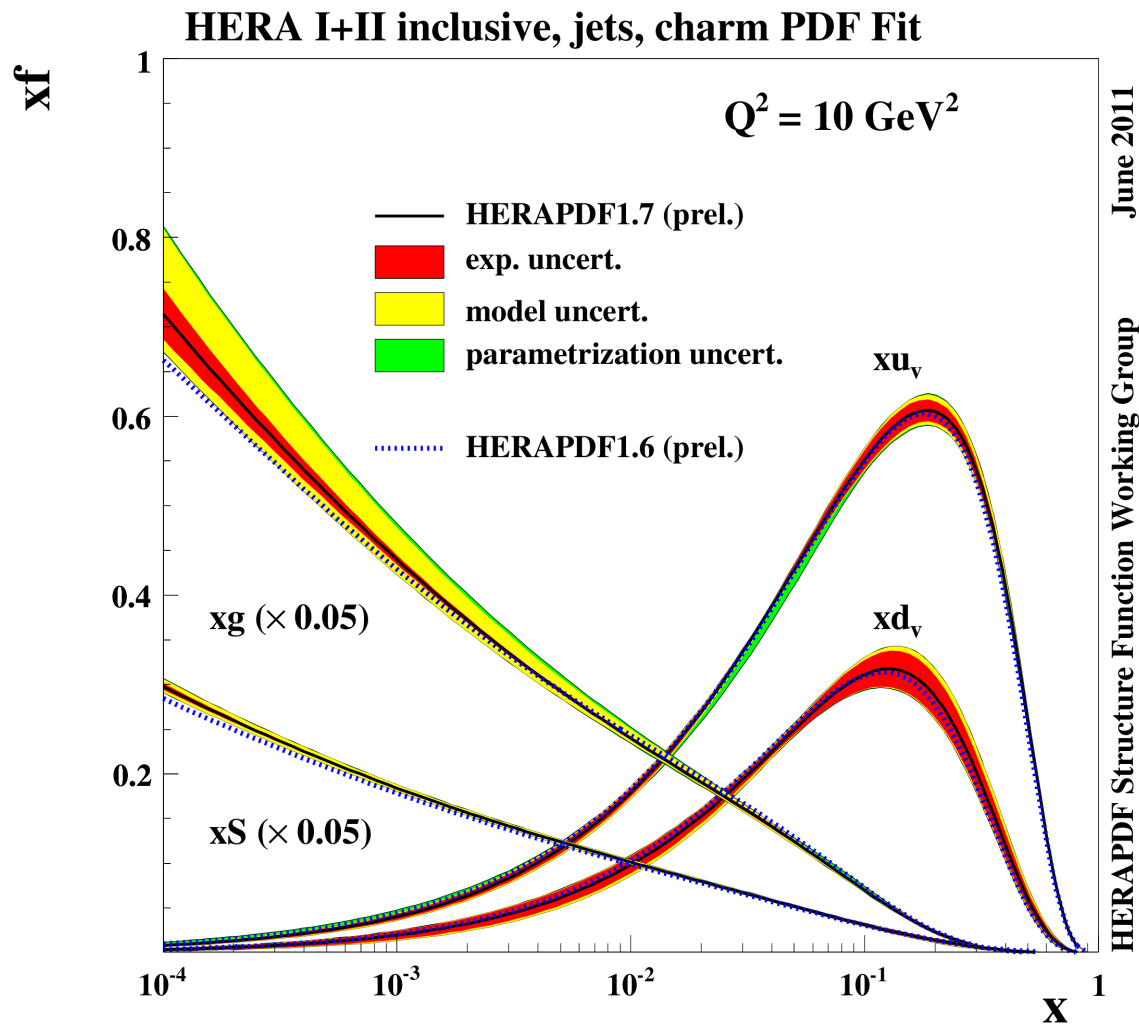


Answer: Point-like partons (a.k.a quarks) !

The age of HERA (1990s)

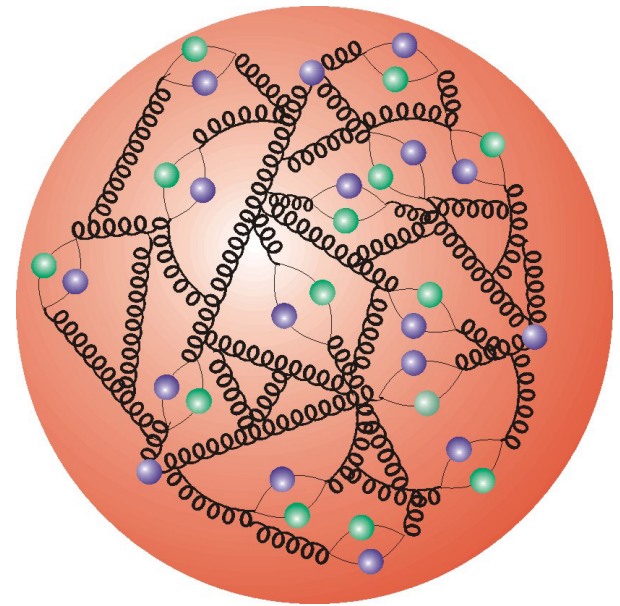


HERA's view of the proton



$$\text{valence quarks} = \int u_v + d_v dx = 3$$

$$\text{gluons} = \int g dx \gtrsim 30$$

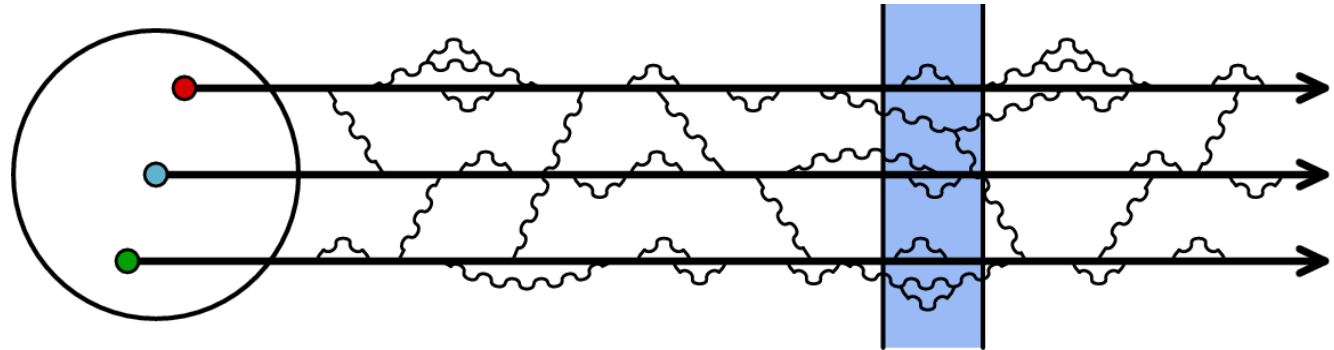


Internal structure of the proton

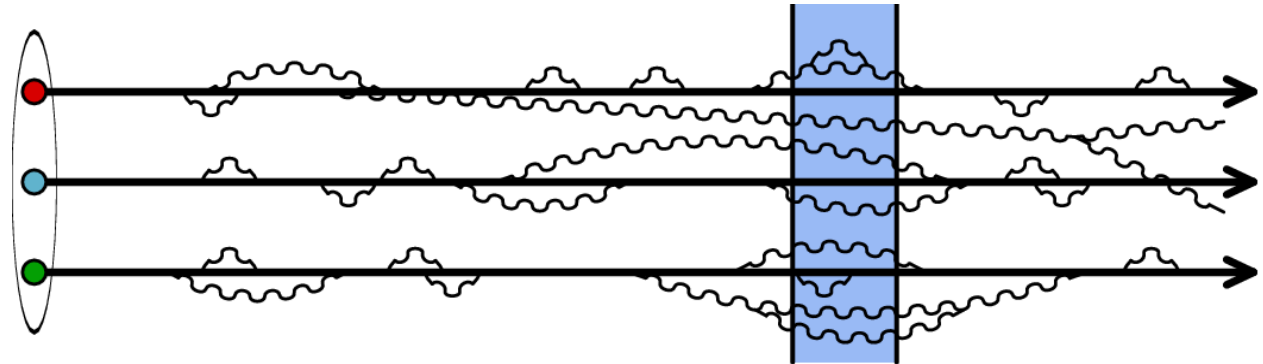
The proton cannot be thought of as a static classical object.

It is made up of quanta that fluctuate into and out of existence:

Low Energy
or
large x



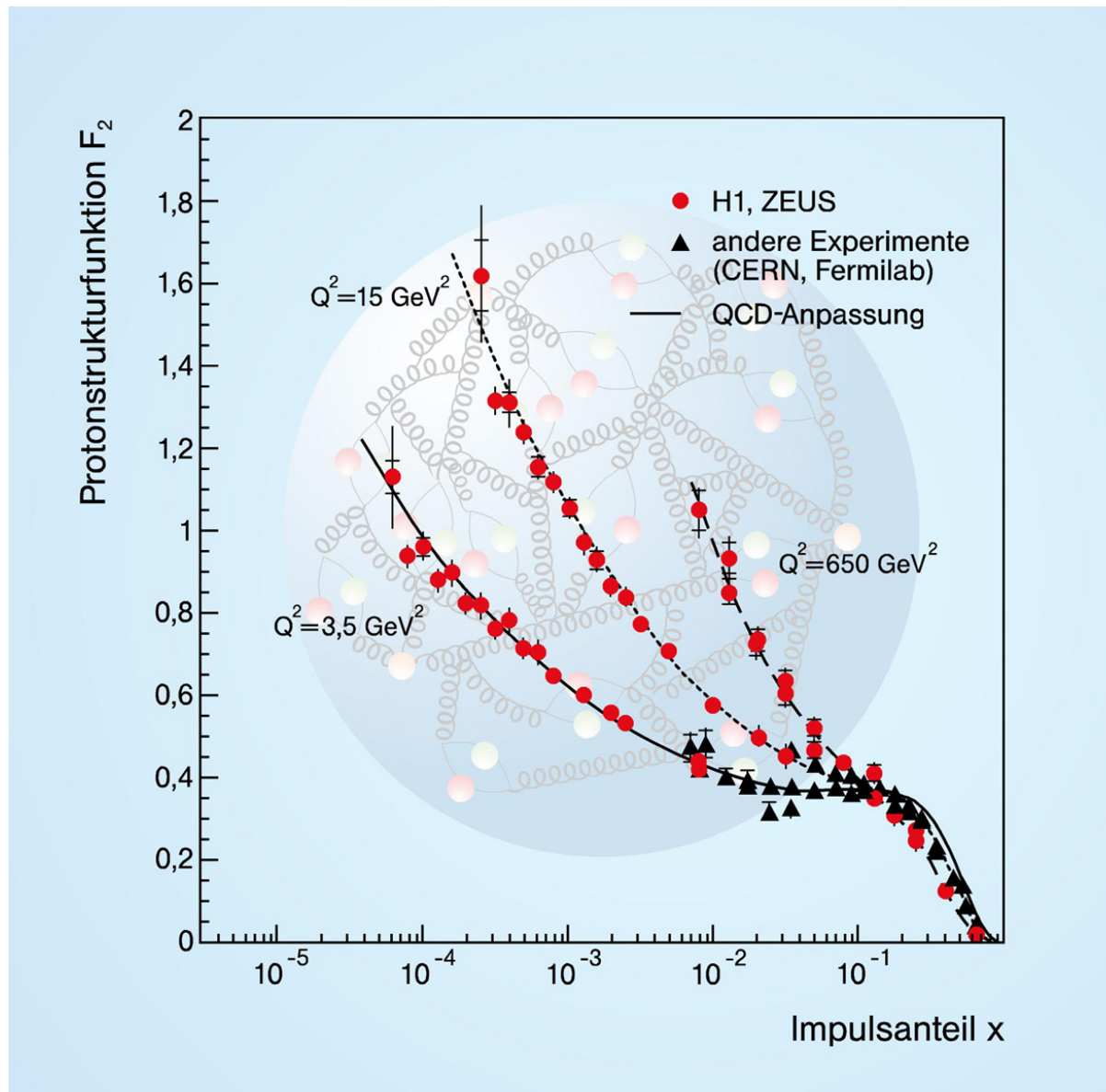
High Energy
or
small x



Wee parton fluctuations time dilated on strong interaction time scales.

These long-lived gluons can further radiate smaller- x gluons ...

The rise at small x



This cannot continue to rise like this forever!

Criteria for Gluon Saturation

1. Transverse gluon density: $\rho \sim \frac{xG_A}{S_\perp} \sim \frac{A xG}{A^{2/3}} \sim A^{1/3} xG$

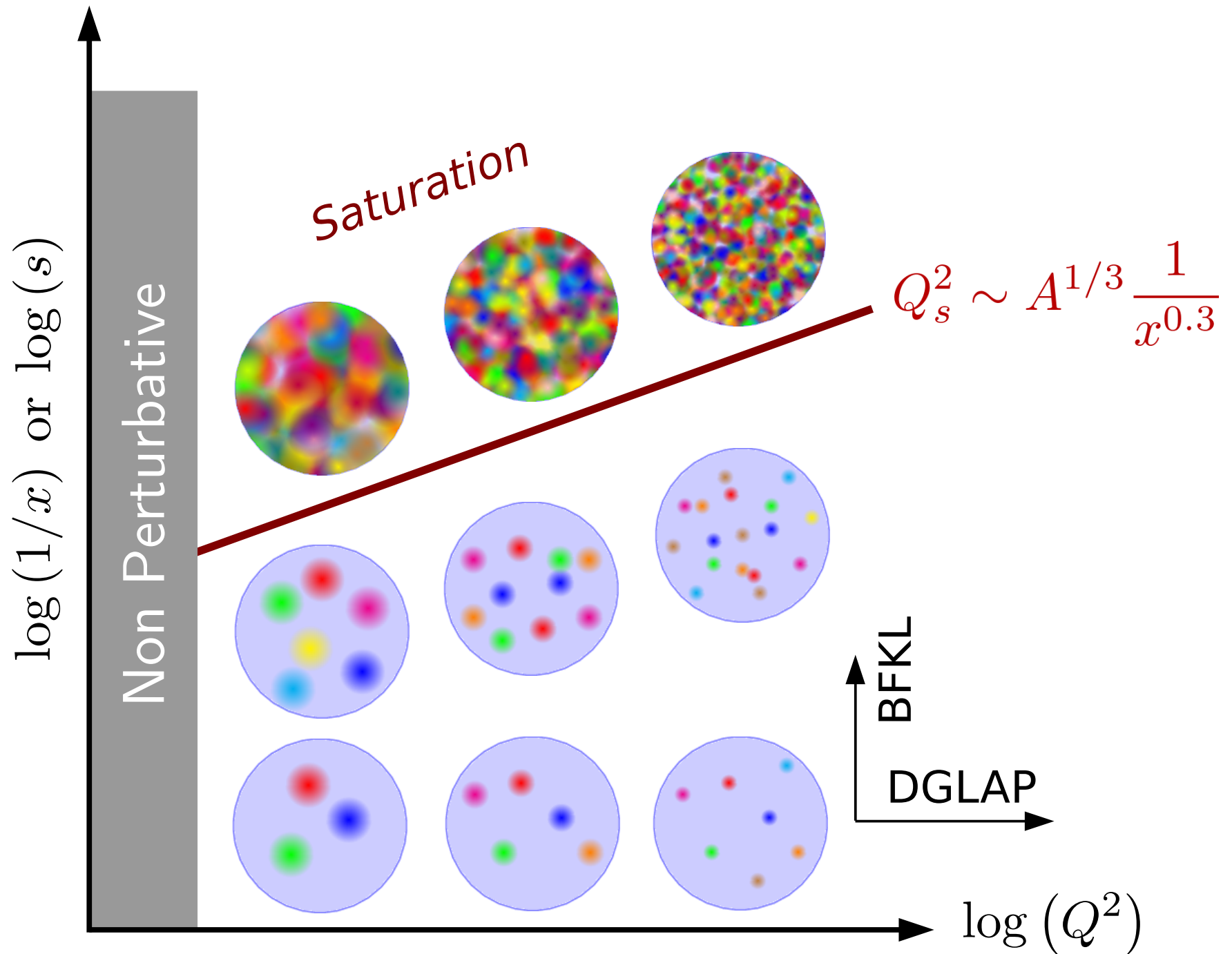
2. Recombination cross-section: $\sigma_{gg \rightarrow g} \sim \frac{\alpha_S}{Q^2}$

3. Saturation Criteria: $\rho \sigma_{gg \rightarrow g} \gtrsim 1$

$$Q_s^2 \sim A^{1/3} xG \sim A^{1/3} x^{-0.3}$$

Saturation scale is a new momentum scale in problem

High Energy Landscape of QCD

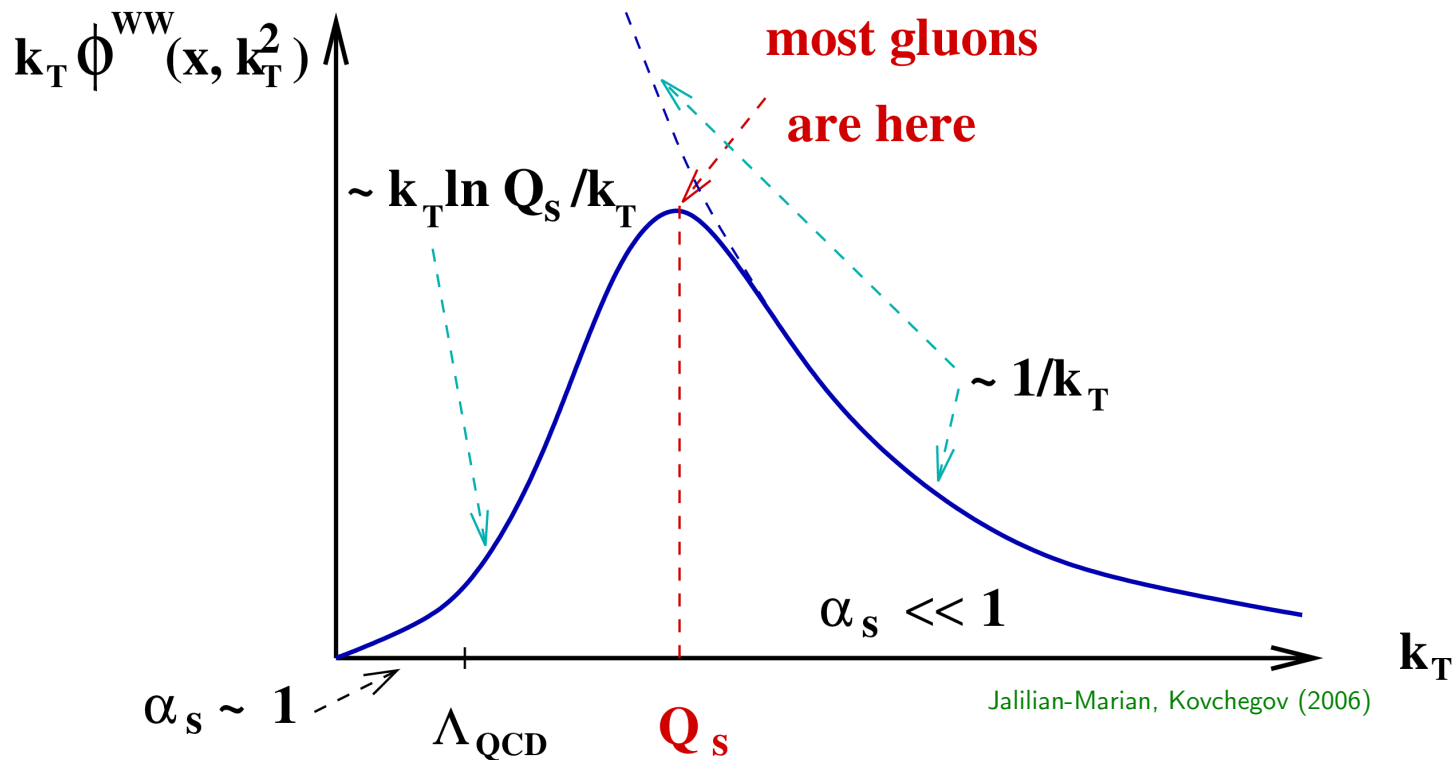


Gluon Saturation

A large nucleus ($A \gg 1$) results in a high occupation of gluons, $\rho \sim A^{1/3}$

and therefore the gluon-field should be classical as realized by McLerran & Venugopalan (1994).

Basic Premise: Large- x partons serve as classical sources for smaller- x gluons.



Many-body high energy QCD: The Color Glass Condensate

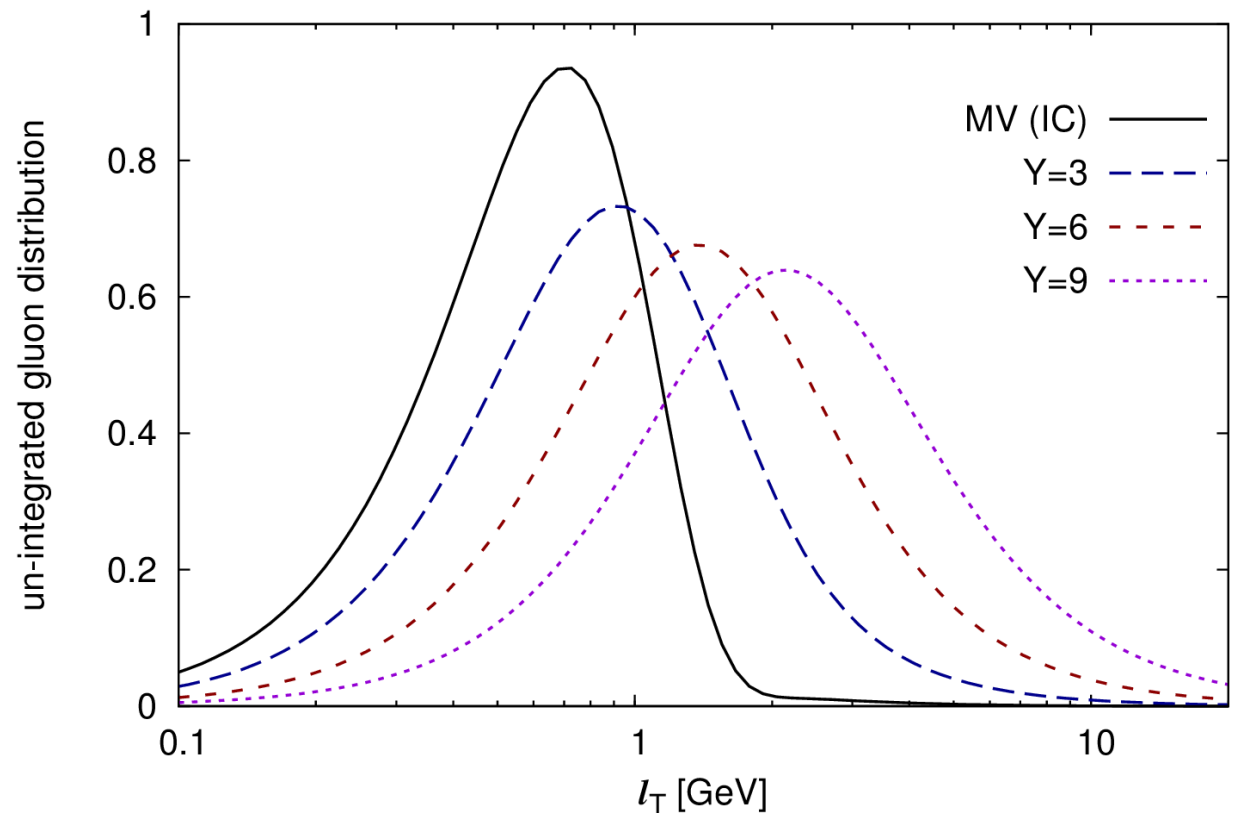
Observables must be independent from how the large- x and small- x degrees of freedom are separated:
Functional Renormalization Group equation (JIMWLK).

For reviews see:

McLerran, Lect. Notes Phys.583:291-334 (2002), [arXiv:hep-ph/0104285](#)

Gelis, Iancu, Jalilian-Marian, Venugopalan:

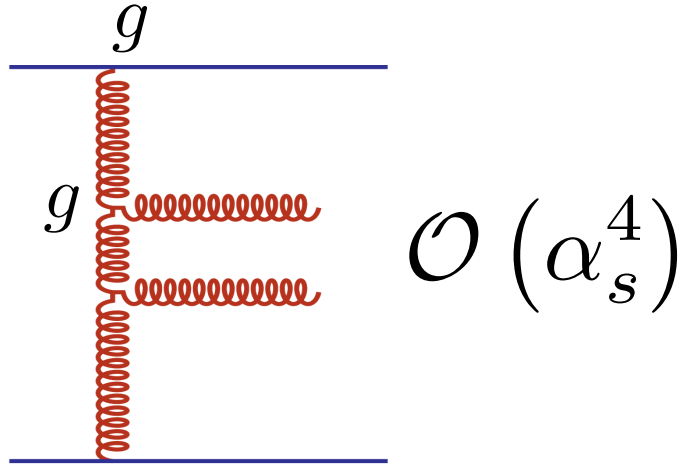
Ann. Rev. Nucl. Part. Sci. (2010), [arXiv: 1002.0333](#)



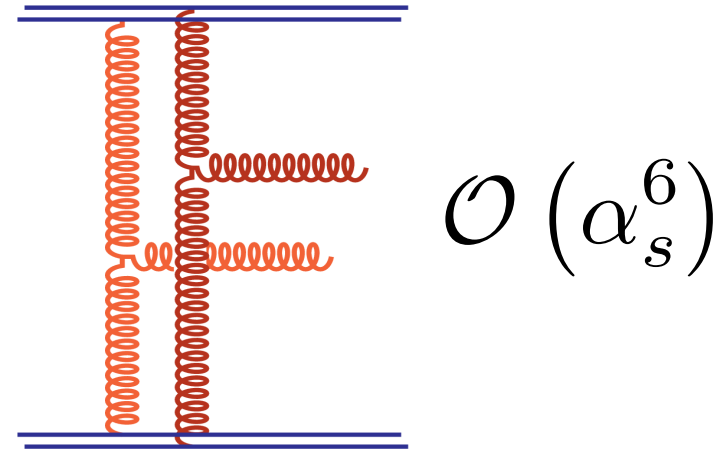
Power counting in QCD: multiparticle production

Low color charge density (min bias):

Jet graph:

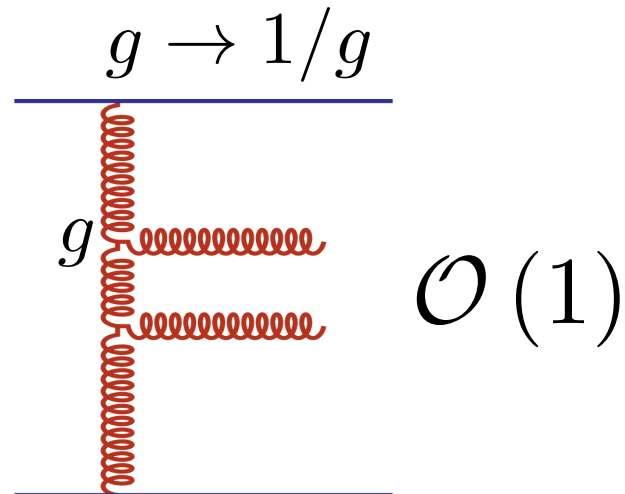


Glasma graph:

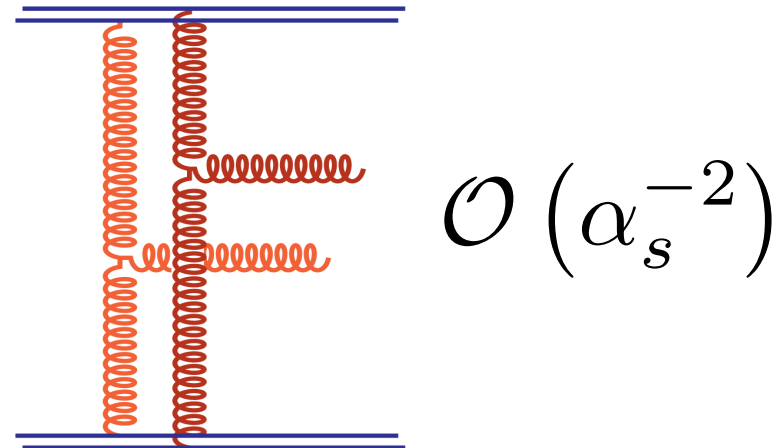


High color charge density (central):

Jet graph:

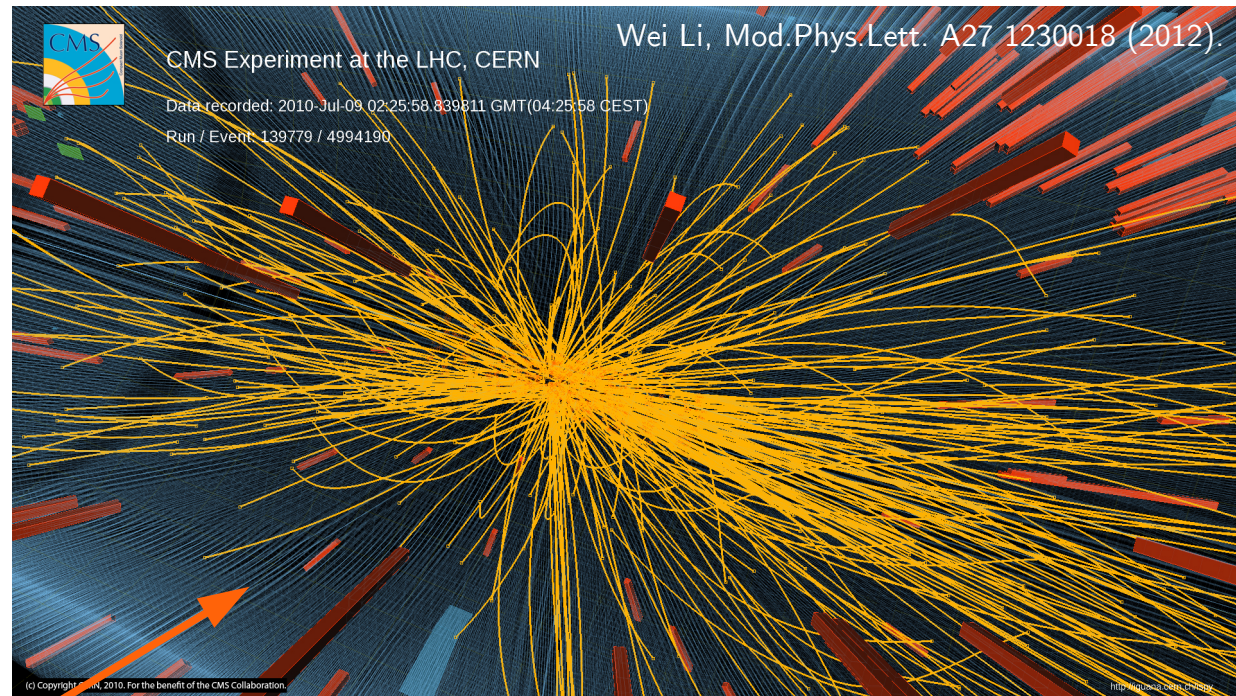
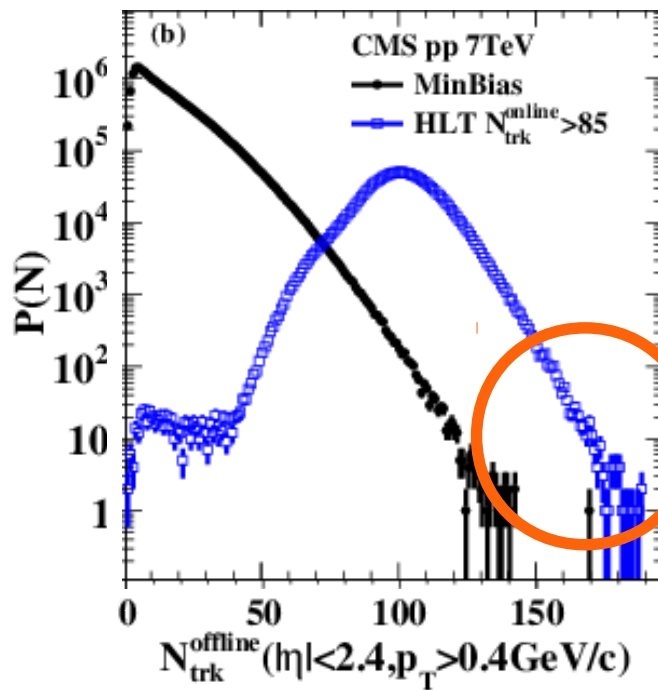


Glasma graph:



Expect α_s^8 enhancement of “Glasma” graph! Is this seen in the data?

First LHC Discovery ! (Sept. 2010)



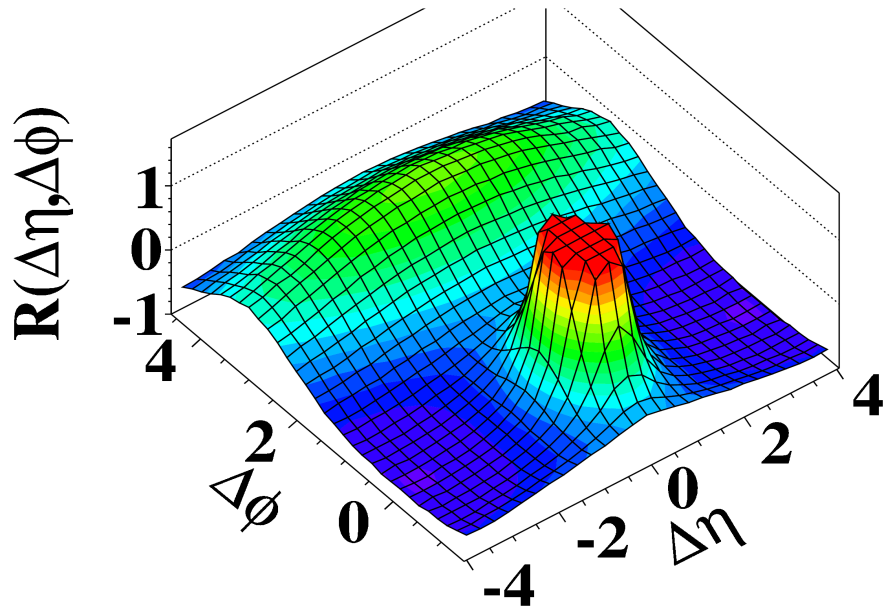
These are ultra-rare events
producing over 100 particles!

Anything interesting going on here?

First LHC Discovery ! (Sept. 2010)

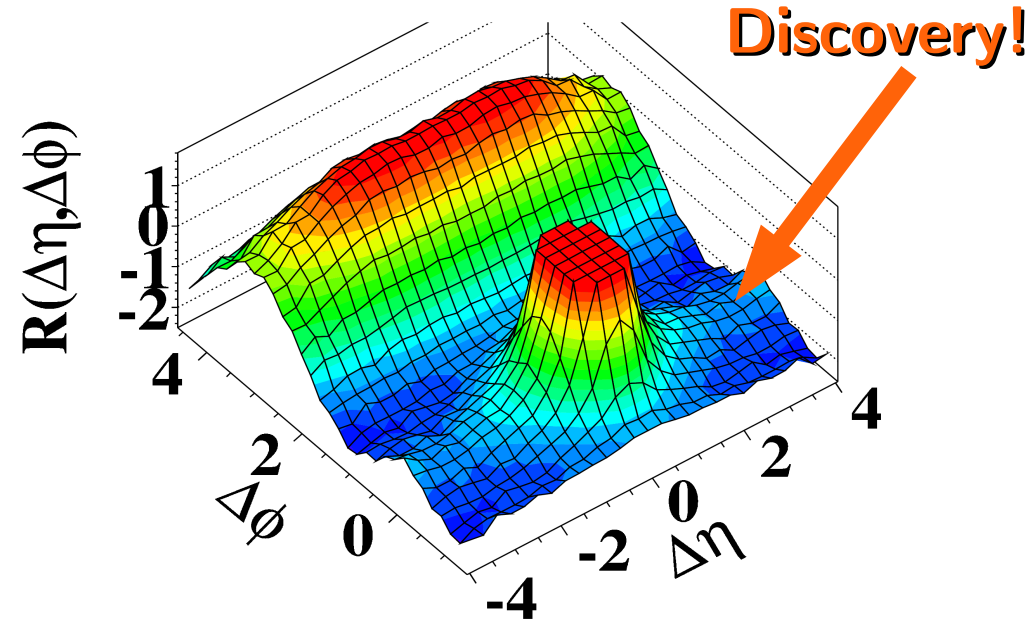
“Normal Event”

(b) CMS MinBias, $1.0\text{GeV}/c < p_T < 3.0\text{GeV}/c$



High Multiplicity Event

(d) CMS $N \geq 110$, $1.0\text{GeV}/c < p_T < 3.0\text{GeV}/c$



CMS Collaboration (Khachatryan, Vardan et al.)
JHEP 1009 (2010) 091
arXiv:1009.4122 [hep-ex]





Particles That Flock: Strange Synchronization Behavior at the Large Hadron Collider

Scientists at the Large Hadron Collider are trying to solve a puzzle of their own making: why particles sometimes fly in sync

By Amir D. Aczel

Scientific American, February (2011).

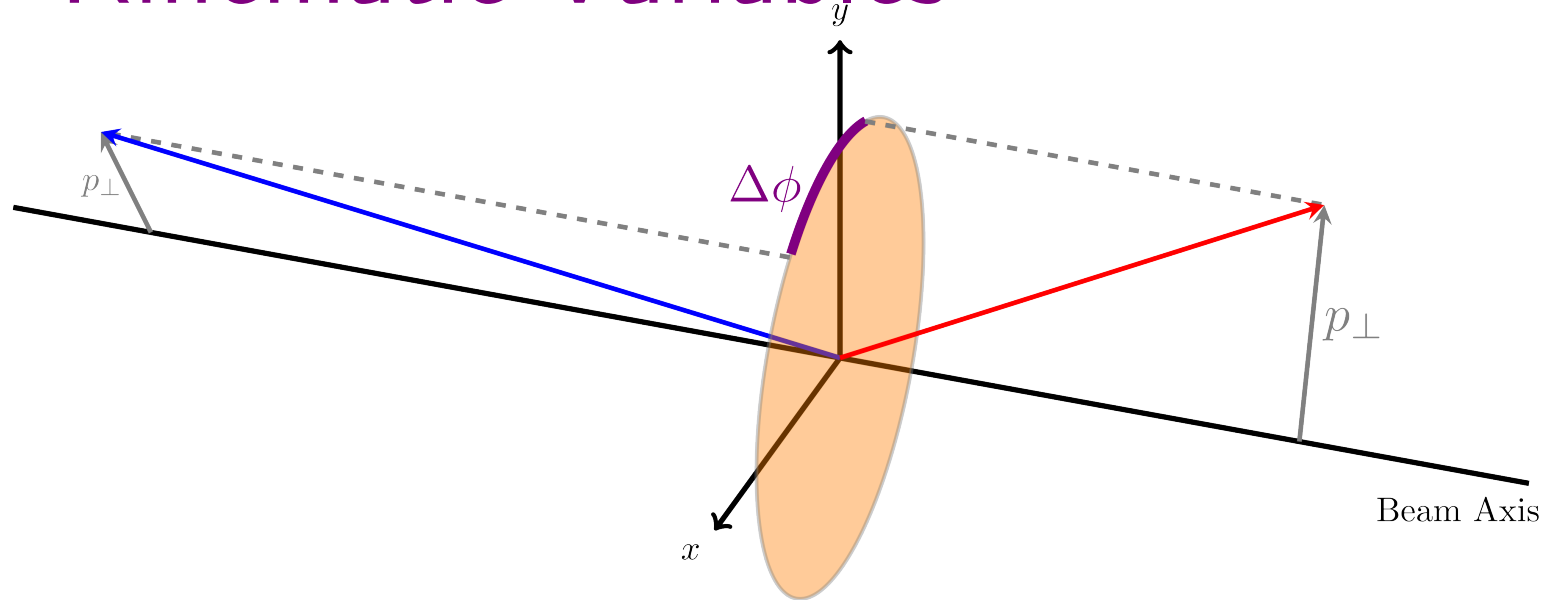
The high-energy collisions of protons in the LHC may be uncovering
“a new deep internal structure of the initial protons”



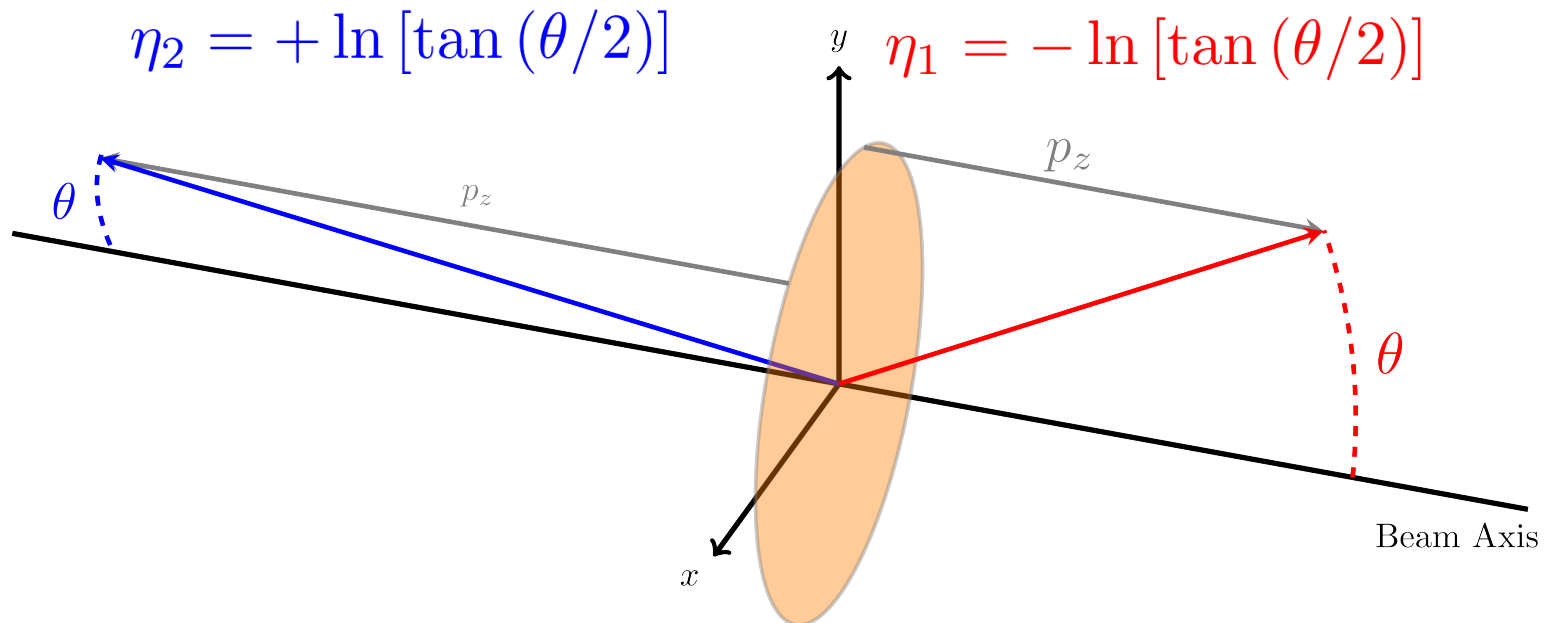
Frank Wilczek (Nobel Prize 2004)

Kinematic Variables

$$\Delta\phi = \phi_2 - \phi_1$$

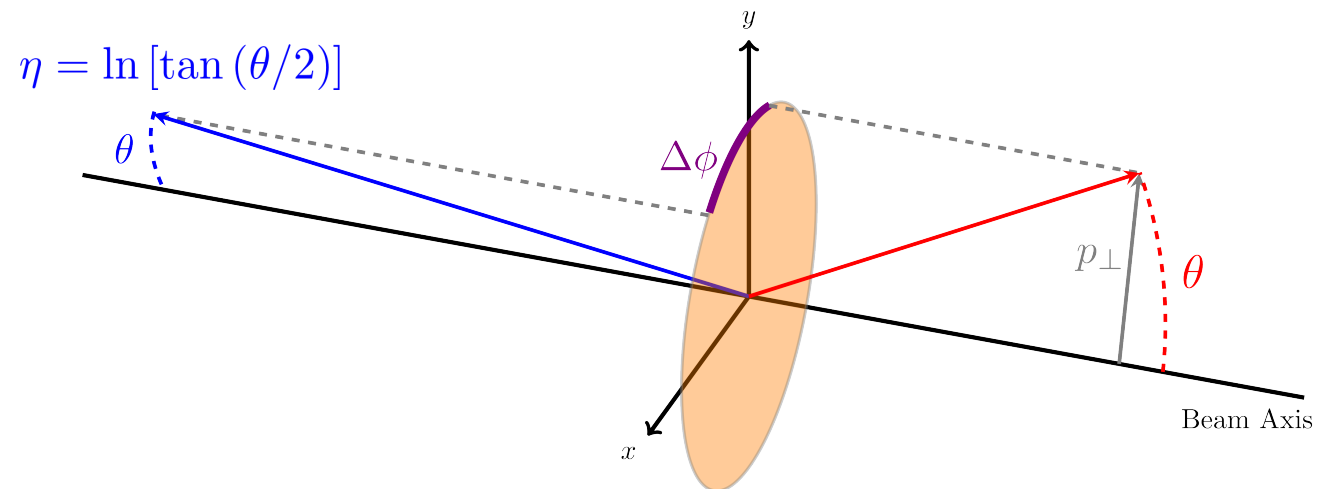
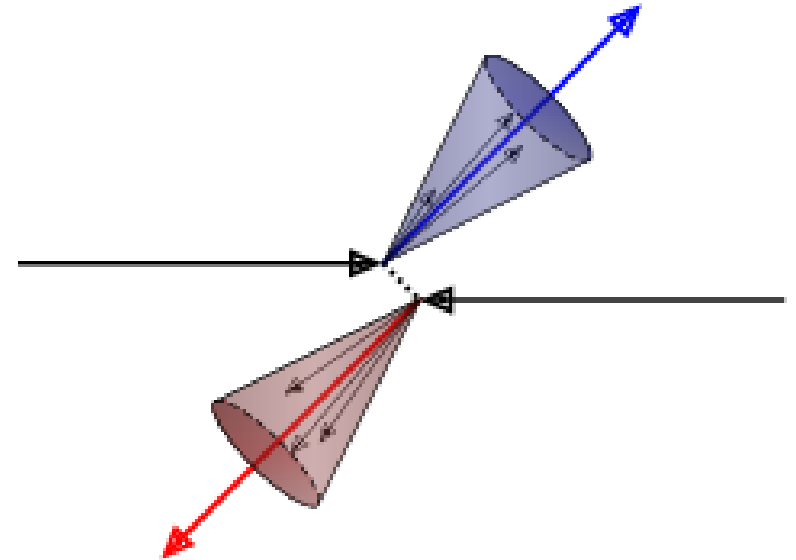
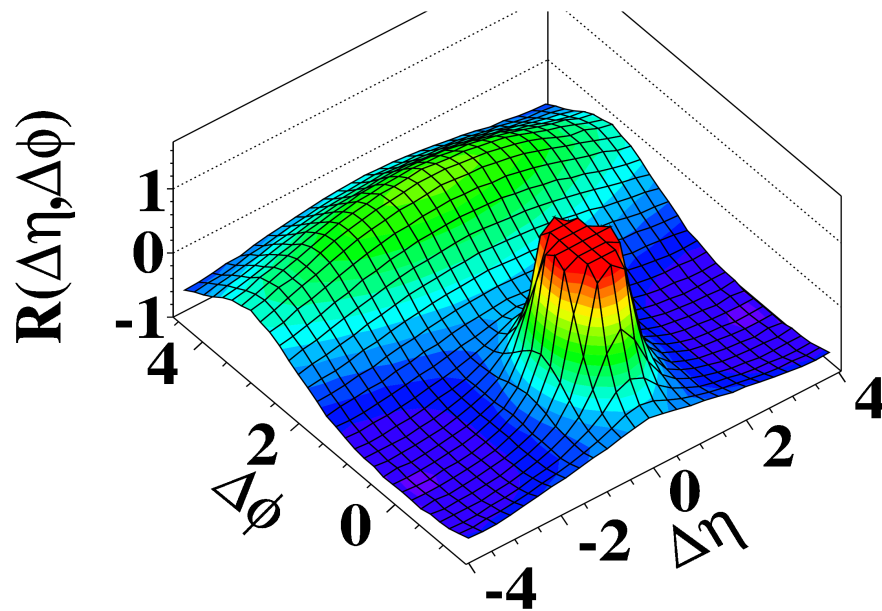


$$\Delta\eta = \eta_2 - \eta_1$$

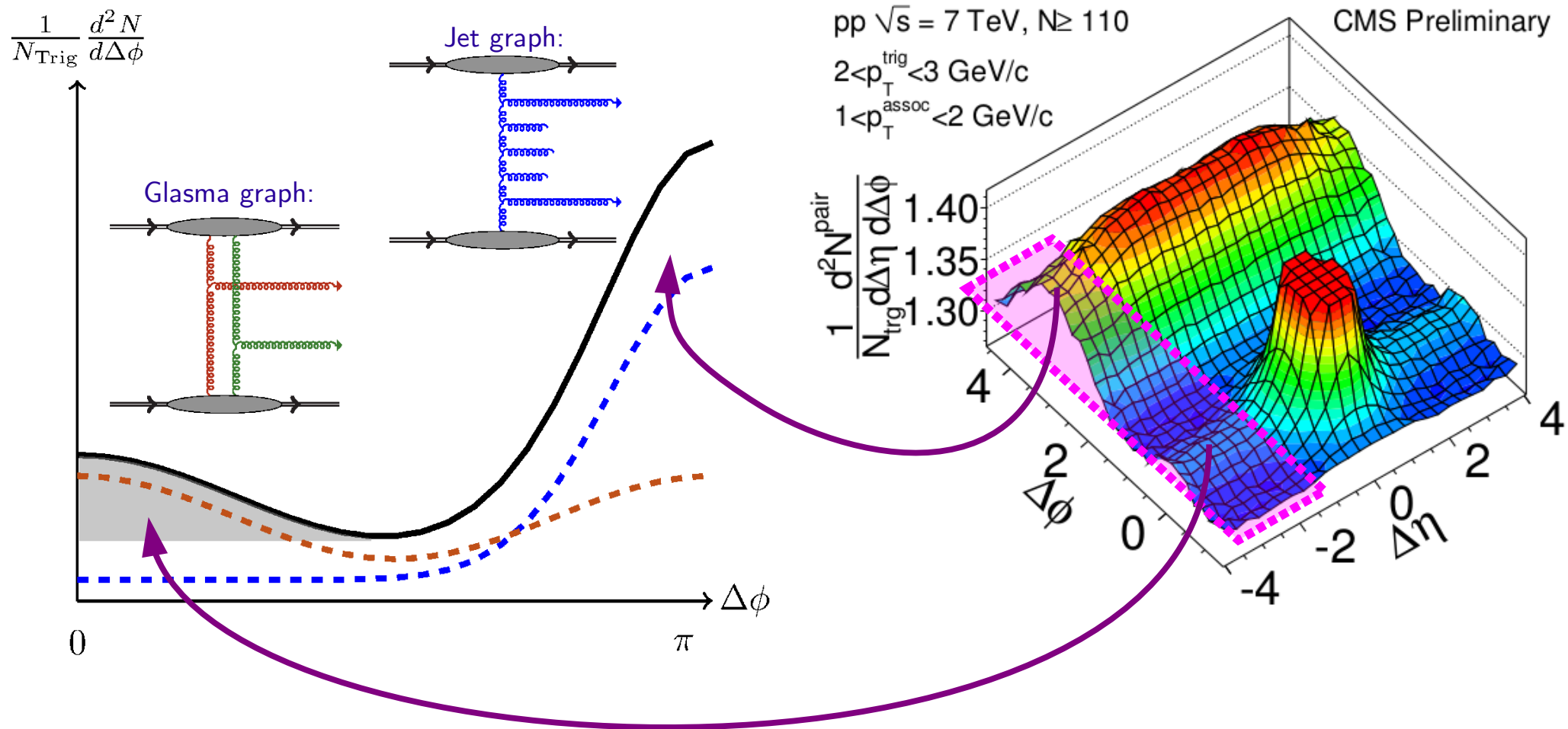


Anatomy of a proton-proton collision

(b) CMS MinBias, $1.0\text{GeV}/c < p_T < 3.0\text{GeV}/c$

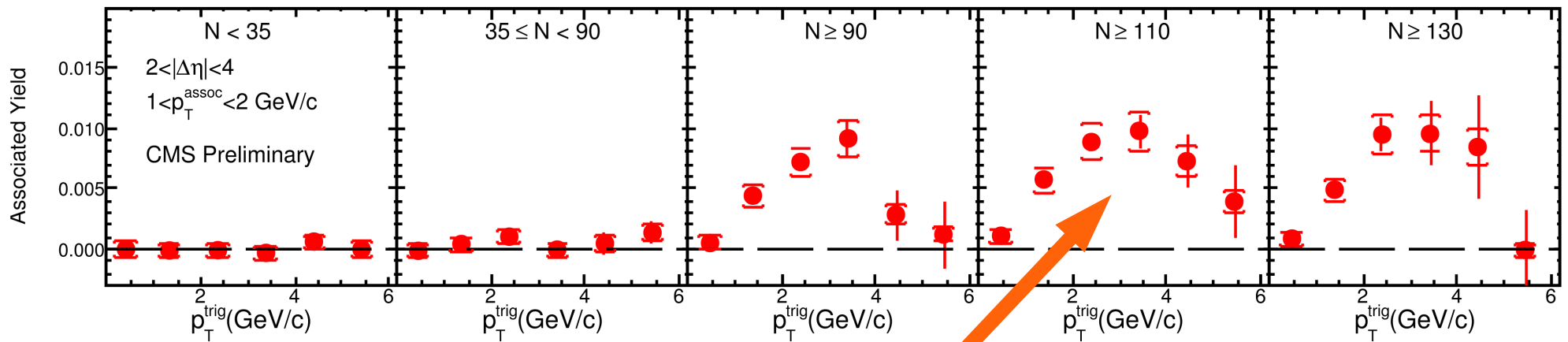
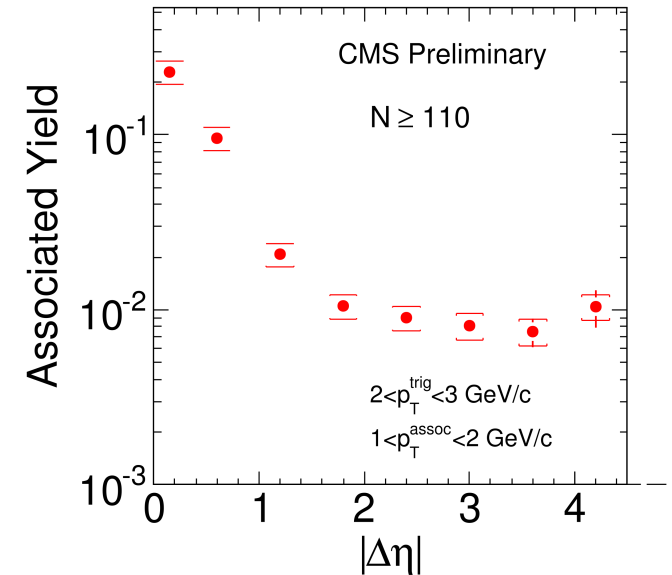


Anatomy of a proton-proton collision



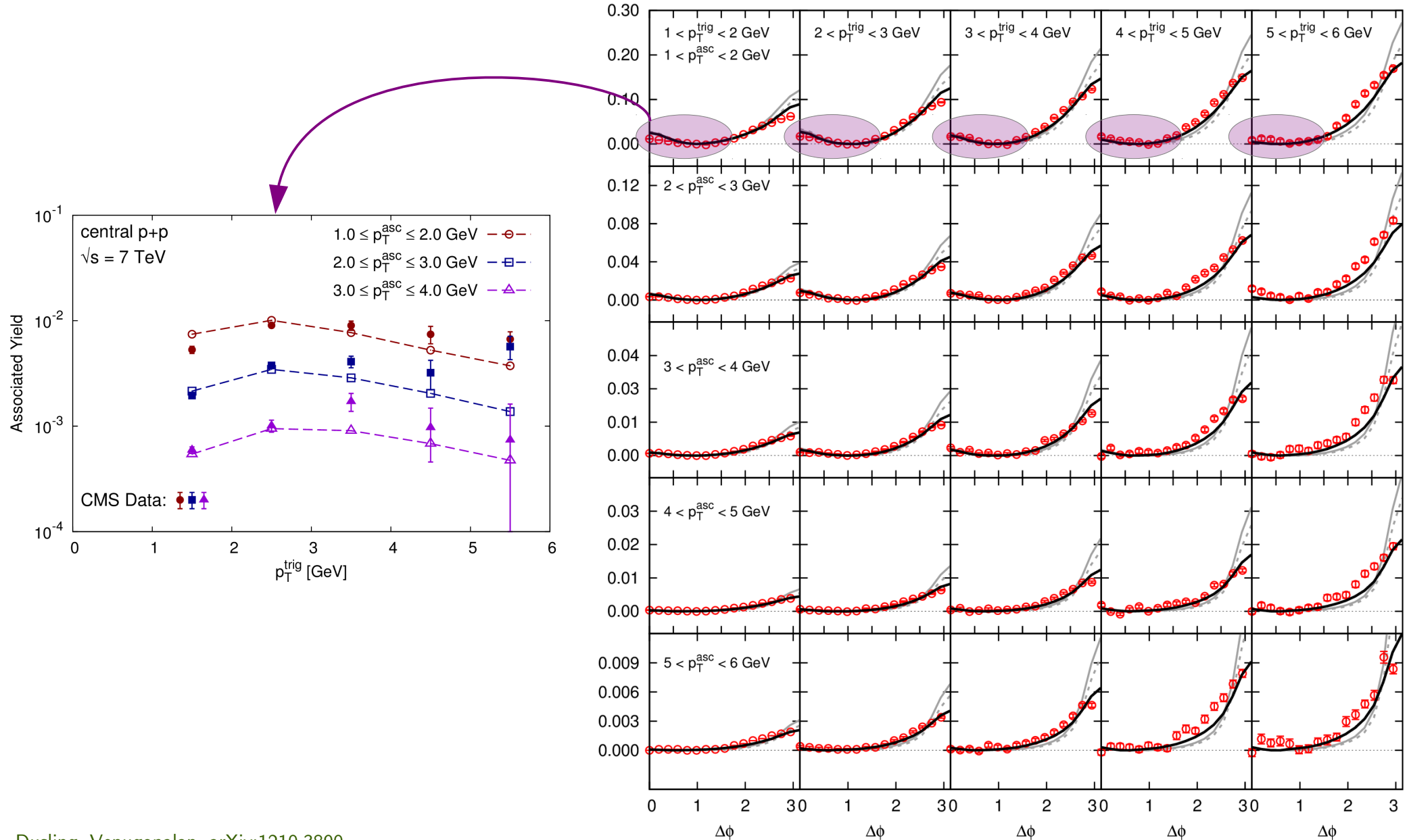
Systematics of the p+p ridge

Ridge persists to large rapidity separations:



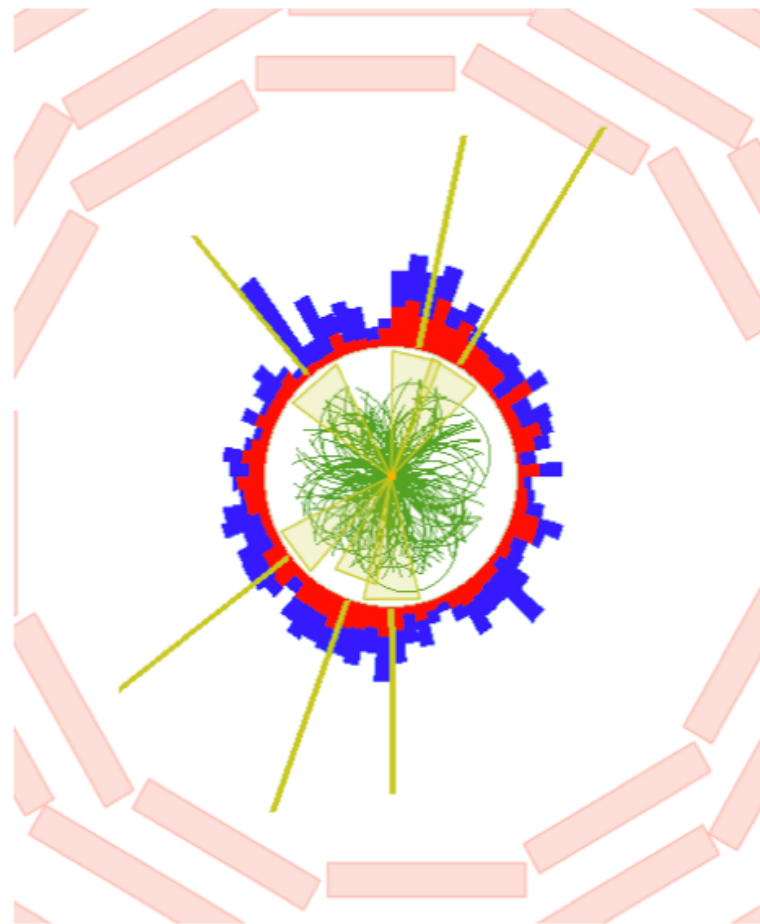
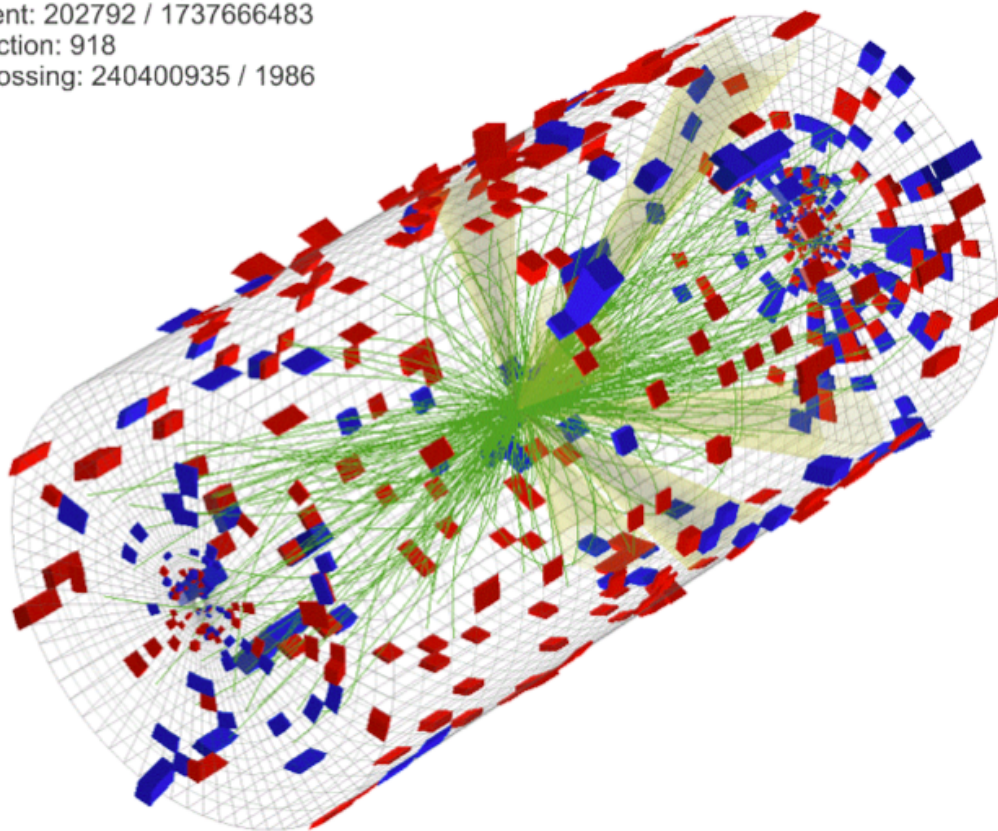
Evidence for a semi-hard scale!

Both Jet and Ridge understood!



p+Pb pilot run (Sept. 2012)

CMS Experiment at LHC, CERN
Data recorded: Thu Sep 13 05:21:23 2012 CEST
Run/Event: 202792 / 1737666483
Lumi section: 918
Orbit/Crossing: 240400935 / 1986

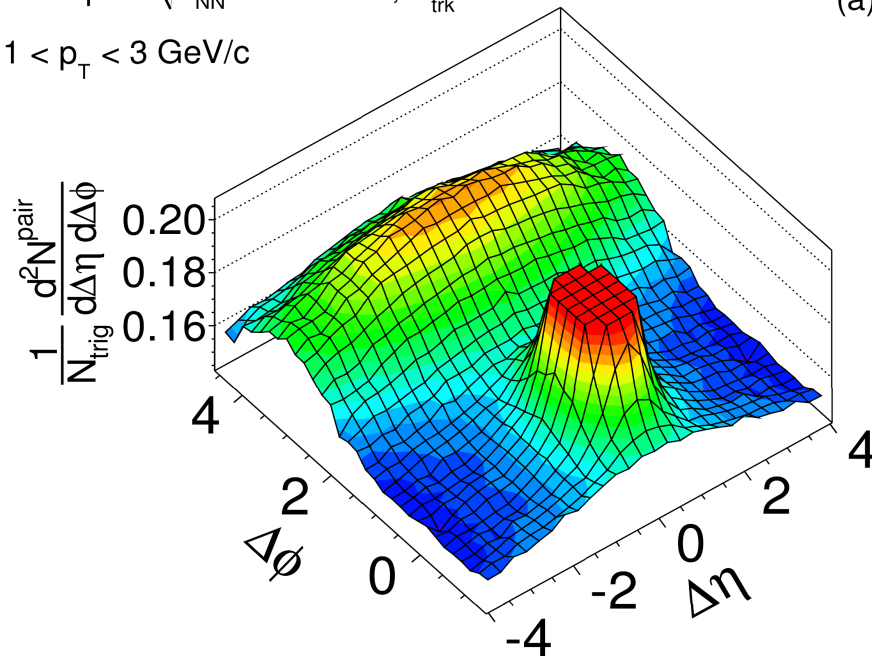


p+Pb pilot run (Sept. 2012)

“Normal Event”

CMS pPb $\sqrt{s_{NN}} = 5.02$ TeV, $N_{\text{trk}}^{\text{offline}} < 35$

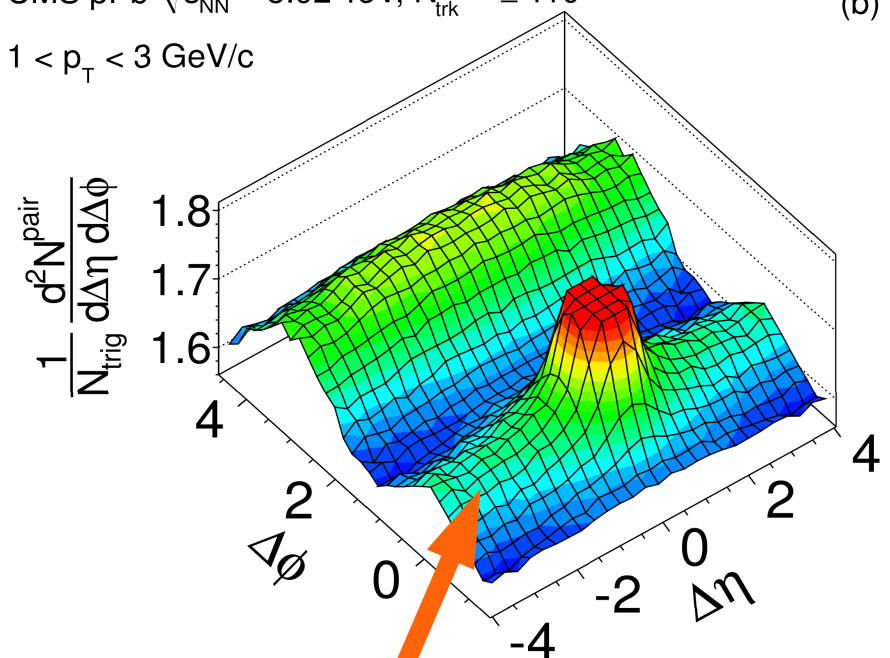
$1 < p_T < 3$ GeV/c



High Multiplicity Event

CMS pPb $\sqrt{s_{NN}} = 5.02$ TeV, $N_{\text{trk}}^{\text{offline}} \geq 110$

$1 < p_T < 3$ GeV/c



Discovery !

Unexpected 'ridge' seen in CMS collision data again

Oct 31, 2012 [6 comments](#)



Lead-proton collisions yield surprising effect in CMS experiment

CMS physicists have once again found a “ridge” in their data, this time in lead–proton collisions.

By Signe Brewster

MAGAZINE OF THE SOCIETY FOR SCIENCE & THE PUBLIC

LHC sees odd behavior in superhot particle soup

Coordinated motion observed in debris from lead-proton collisions



By Andrew Grant

Web edition: December 5, 2012

Print edition: January 12, 2013; Vol.183 #1 (p. 12)

MITnews

Lead-proton collisions yield surprising results

Unexpected data from the Large Hadron Collider suggest the collisions may be producing a new type of matter.

Anne Trafton, MIT News Office

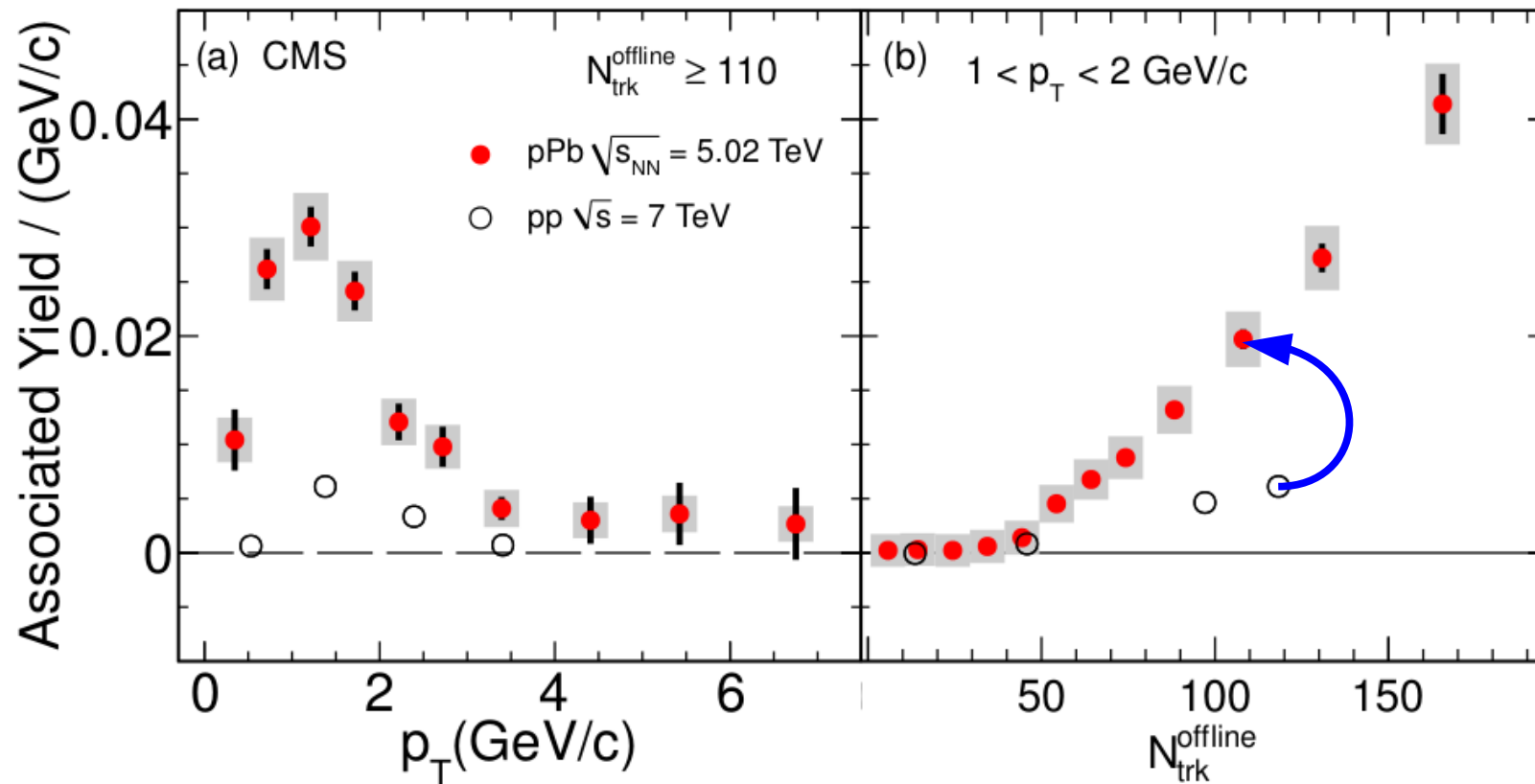
November 27, 2012

DRUDGE REPORT

Data from Large Hadron Collider suggest collisions producing new type of matter...

After 19 years of marriage, husband discovers wife was once a man...

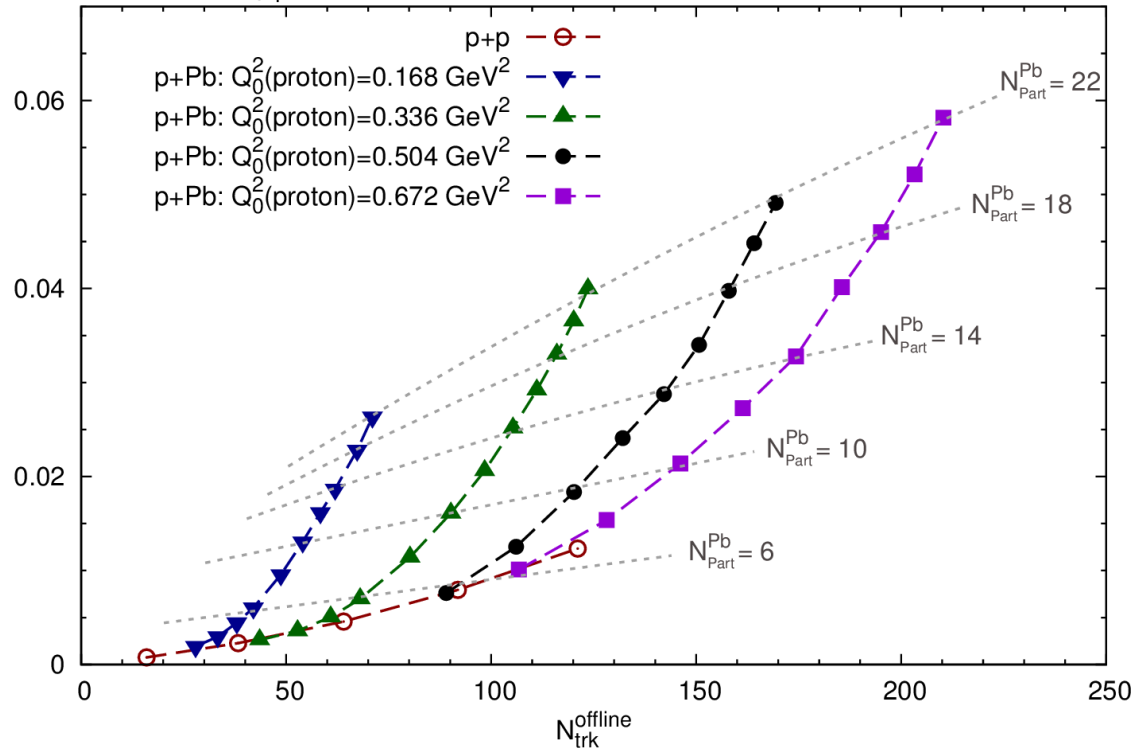
Systematics in p+Pb



Similar systematics BUT factor of 4 larger for same N_{trk} (i.e. density)

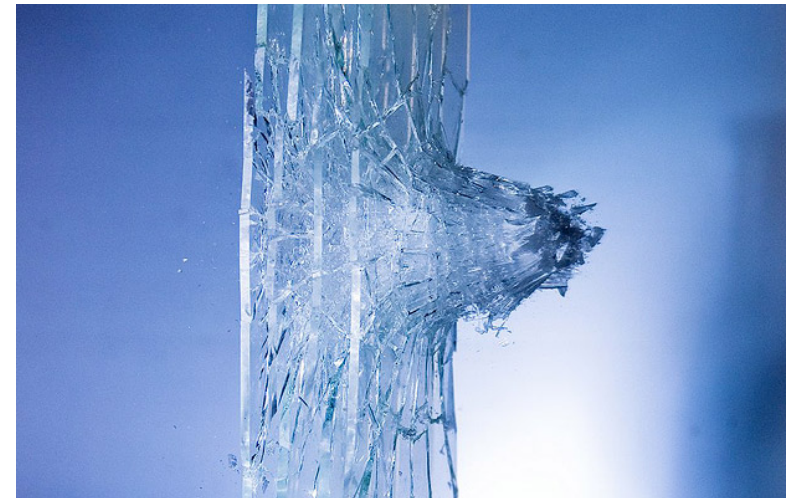
Understanding the Ridge

Associated Yield ($1.0 \leq p_T [\text{GeV}] \leq 2.0$)



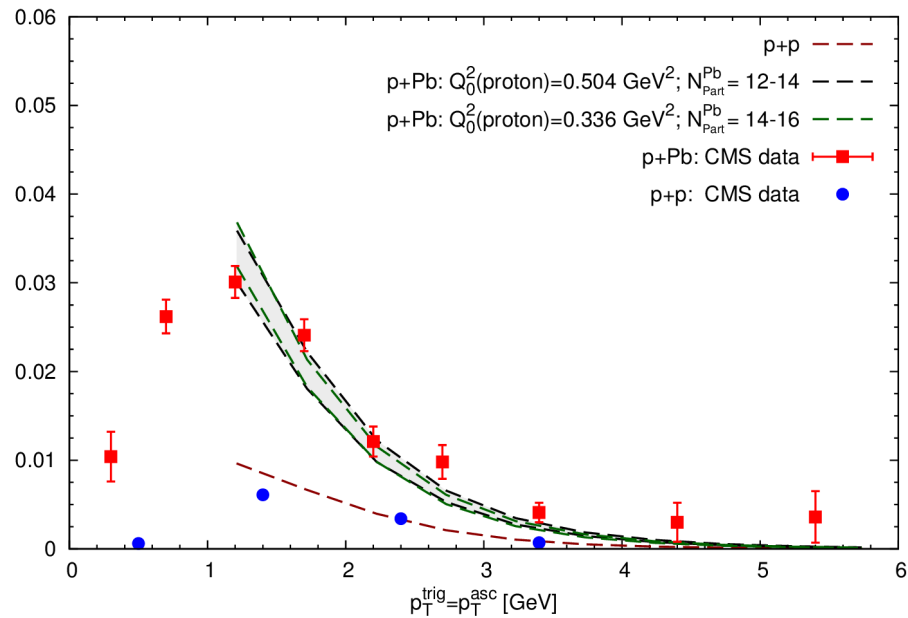
$$Q_0^2(\text{lead}) = N_{\text{part}}^{\text{Pb}} \cdot 0.168 \text{ GeV}^2$$

Like a bullet through a pane of glass:

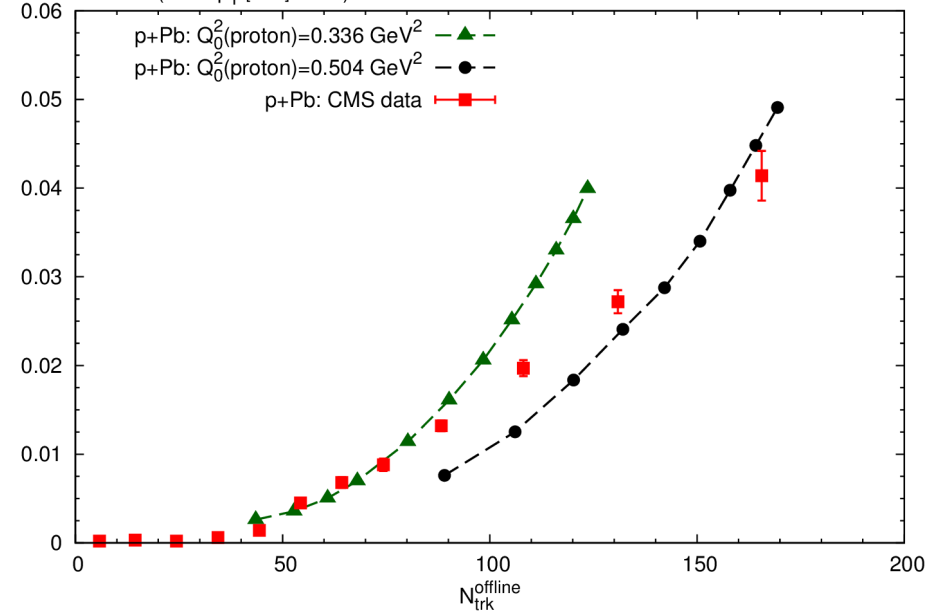


CMS p+Pb data understood!

Associated Yield

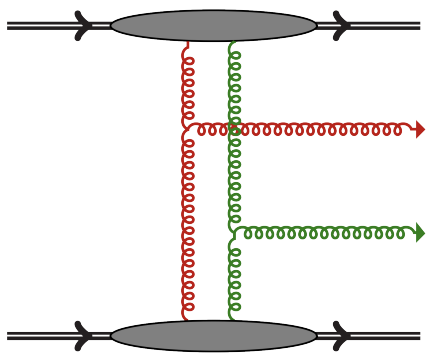


Associated Yield ($1.0 \leq p_T$ [GeV] ≤ 2.0)



Understanding the Ridge

The origin of the ridge is a subtle form of quantum entanglement:



$$\propto S_{\perp} \int d^2 k_{\perp} \Phi_A^2(\mathbf{k}_T) \Phi_B(|\mathbf{p}_T - \mathbf{k}_T|) \Phi_B(|\mathbf{q}_T - \mathbf{k}_T|)$$

Cauchy-Schwarz Inequality:

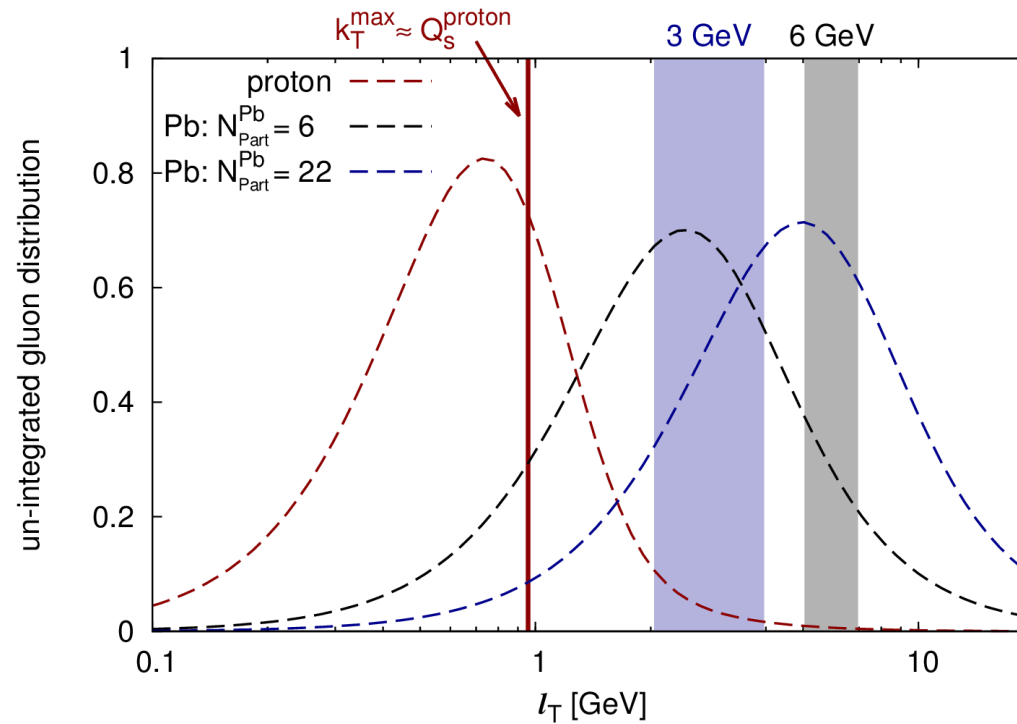
$$\int d^2 k_{\perp} \Phi_A^2(\mathbf{k}_T) \Phi_B(|\mathbf{p}_T - \mathbf{k}_T|) \Phi_B(|\mathbf{q}_T - \mathbf{k}_T|) \leq \int d^2 k_{\perp} \Phi_A^2(\mathbf{k}_T) \Phi_B^2(|\mathbf{p}_T - \mathbf{k}_T|)$$

Equality satisfied if and only if: $\Phi(|\mathbf{p}_T + \mathbf{k}_T|) \propto \Phi(|\mathbf{q}_T + \mathbf{k}_T|)$

Expect collimation on very general grounds

Understanding the Ridge

Ratio of Peak to Pedestal: $CY \propto \frac{\int d^2k_{\perp} \Phi_A^2(\mathbf{k}_T) \Phi_B^2(|\mathbf{p}_T - \mathbf{k}_T|)}{\int d^2k_{\perp} \Phi_A^2(\mathbf{k}_T) \Phi_B(|\mathbf{p}_T - \mathbf{k}_T|) \Phi_B(|\mathbf{p}_T + \mathbf{k}_T|)}$

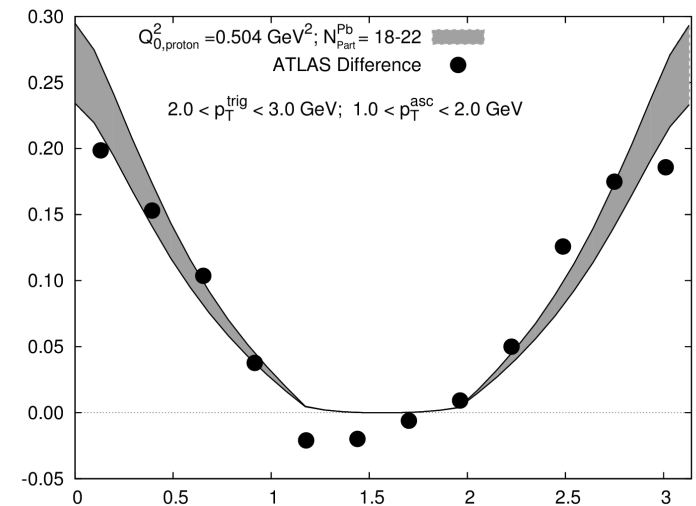
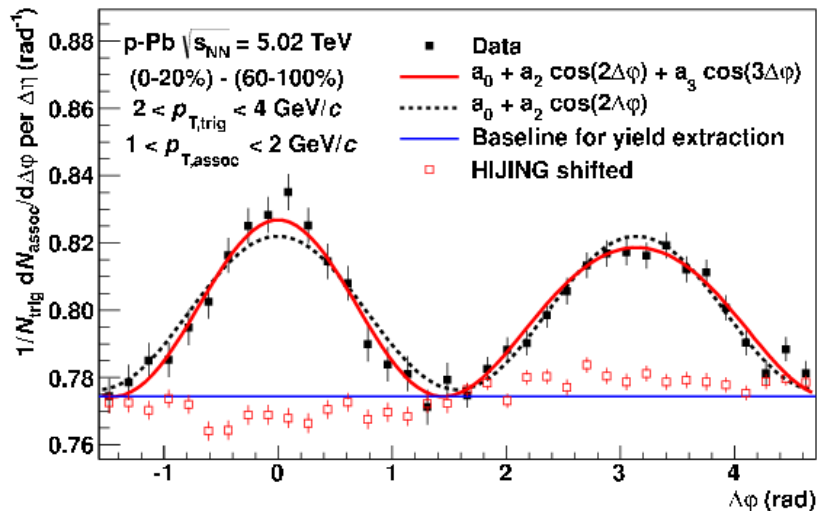


$$CY \propto \frac{\Phi_B(Q_B)}{\Phi_B\left(\sqrt{2p_T^2 + 2Q_A^2 - Q_B^2}\right)} \xrightarrow{Q_B \gg Q_A} 1 + \frac{Q_B^2}{Q_A^2}$$

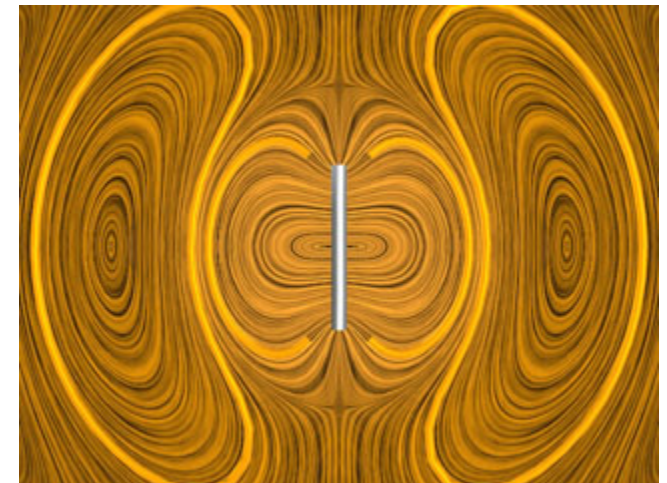
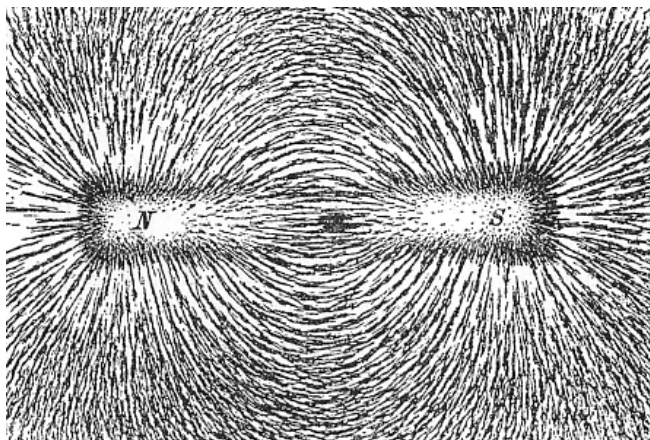
Collimation sensitive to detailed structure of nuclear wavefunction

News from ALICE and ATLAS:

ALICE and ATLAS manage to subtract the jet-contribution leaving behind the raw signal from the Glasma flux tube:



Analogous to:



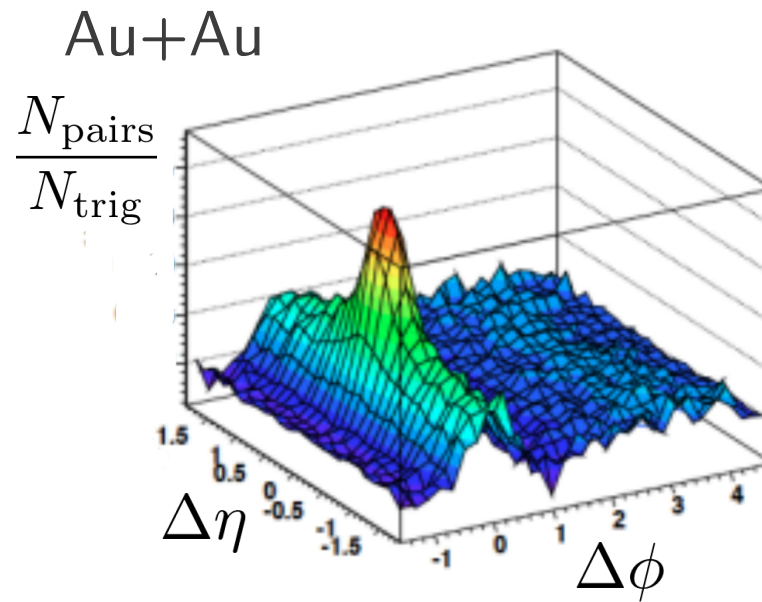
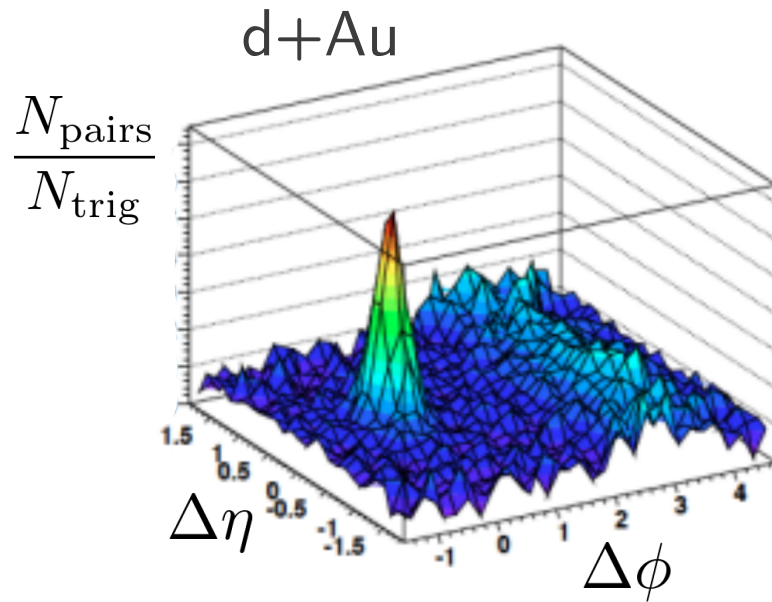
Summary

The LHC has made a remarkable discovery of a novel collimation between two particles flying in opposite directions in ultra-rare high multiplicity events.

1. Is this the smoking gun for saturation ?
2. Are we are imaging the decay of a QCD flux-tube or string ?
3. Are we probing universal dynamics of the proton's wavefunction ?

Backup

The Heavy-Ion Ridge



Dan Magestro, STAR, Hard Probes 2004
Jorn Putschke, STAR, Quark Matter 2006

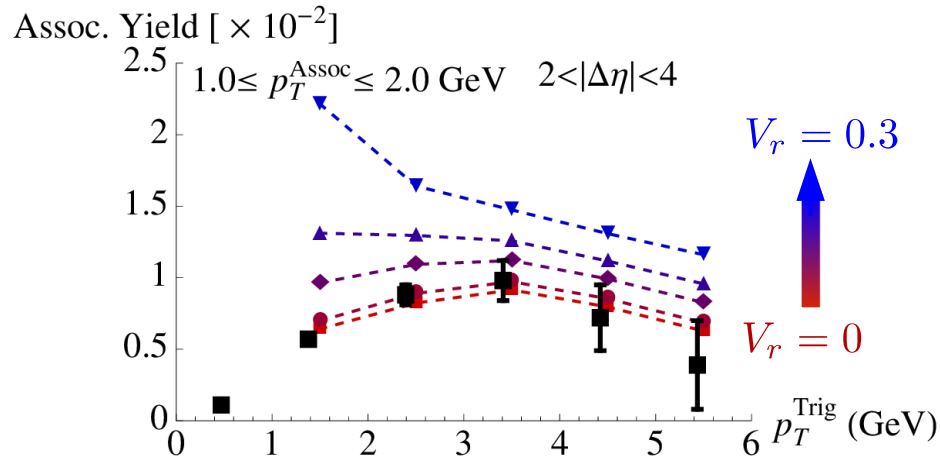
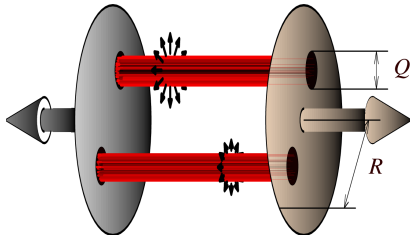
The ridge phenomenon was first discovered in heavy-ion collisions.

p+p

vs

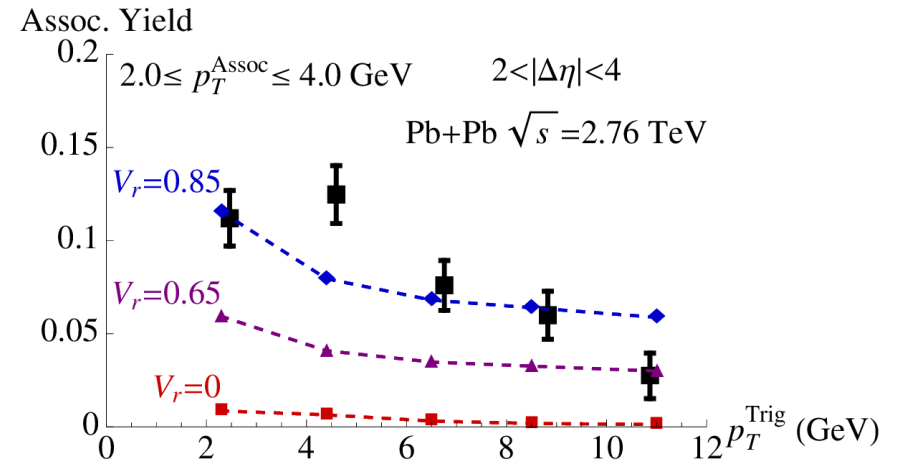
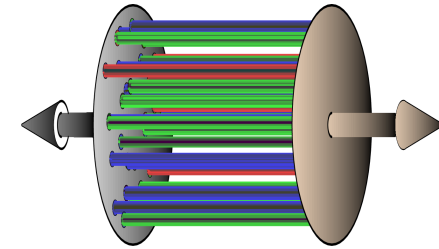
A+A

In p+p we are seeing the intrinsic collimation from a single flux tube



Increasing transverse flow in p+p creates a discrepancy with data.

In A+A there are many such tubes each with an intrinsic correlation enhanced by flow

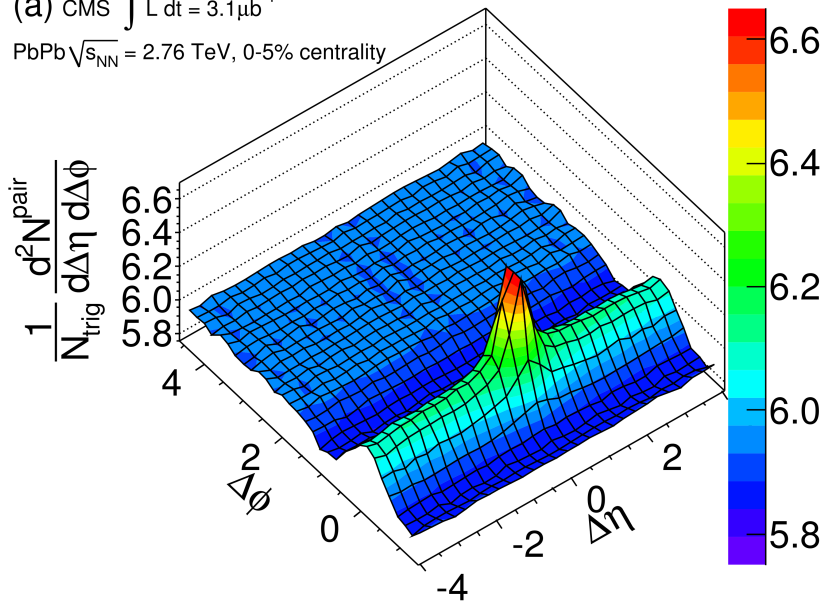


Yet, transverse flow is needed to explain identical measurements in Pb+Pb

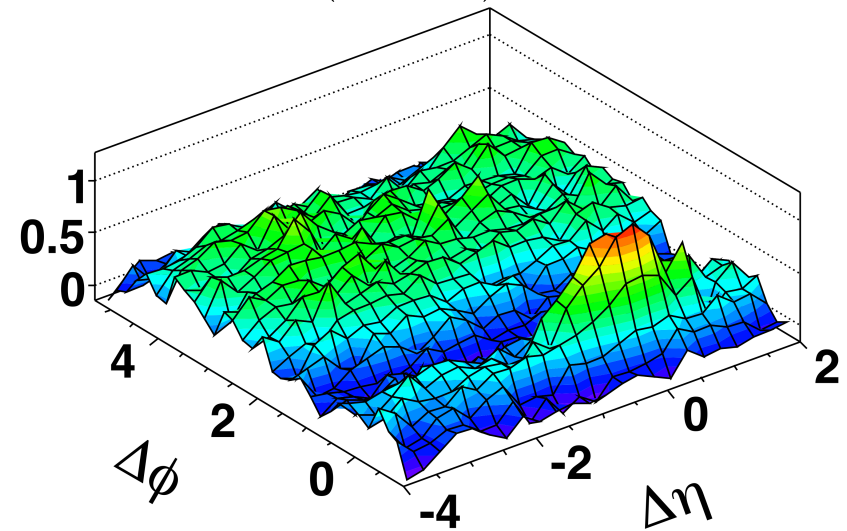
Are we sure the A+A ridge is probing the nuclear wavefunction?

Heavy-Ion Ridge

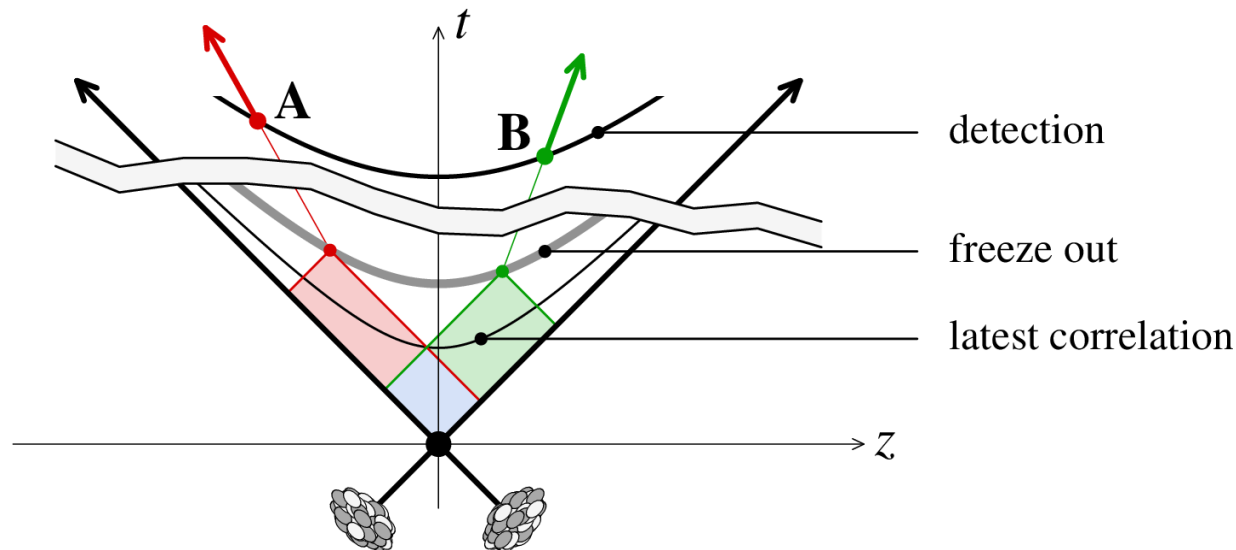
(a) CMS $\int L dt = 3.1 \mu\text{b}^{-1}$
PbPb $\sqrt{s_{NN}} = 2.76 \text{ TeV}$, 0-5% centrality



PHOBOS (Au+Au) $\sqrt{s} = 200 \text{ GeV}$

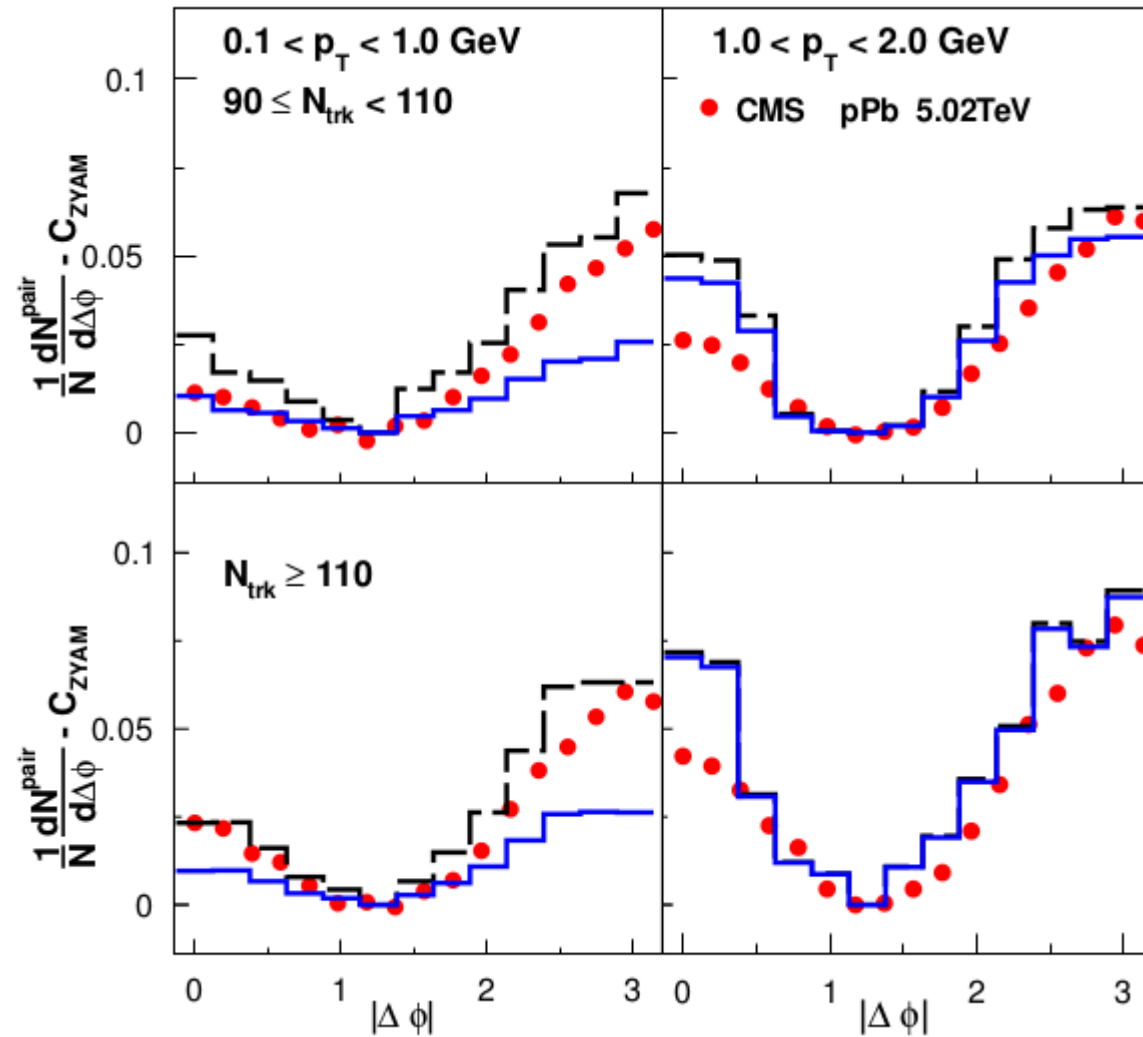


**The correlation is long range in rapidity.
Causality dictates the correlation formed early.**



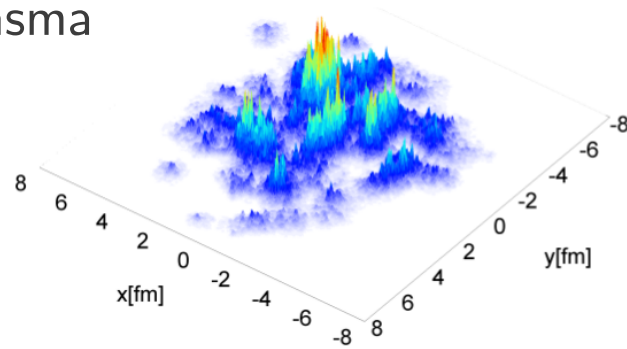
Dumitru, Gelis,
McLerran, Venugopalan,
NPA810 (2008) 91-108.
Dusling, Gelis,
Lappi, Venugopalan,
NPA836 (2010) 159-182.
Ma, Wang,
PRL 106 (2011) 162301.

Hydro calculation for p+Pb ridge

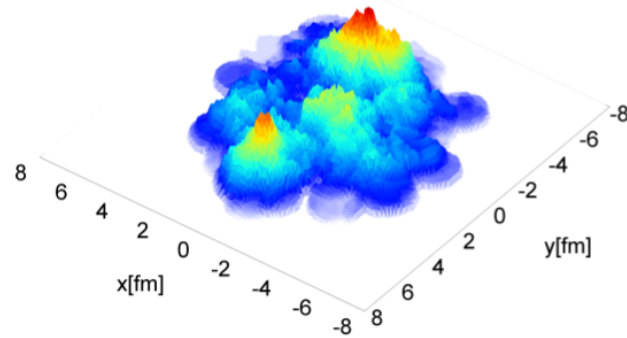


CGC + Hydro

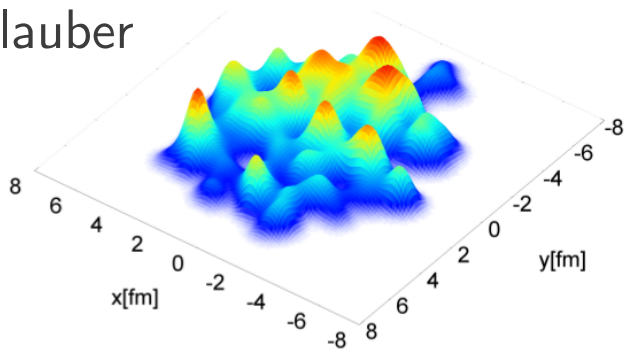
IP-Glasma



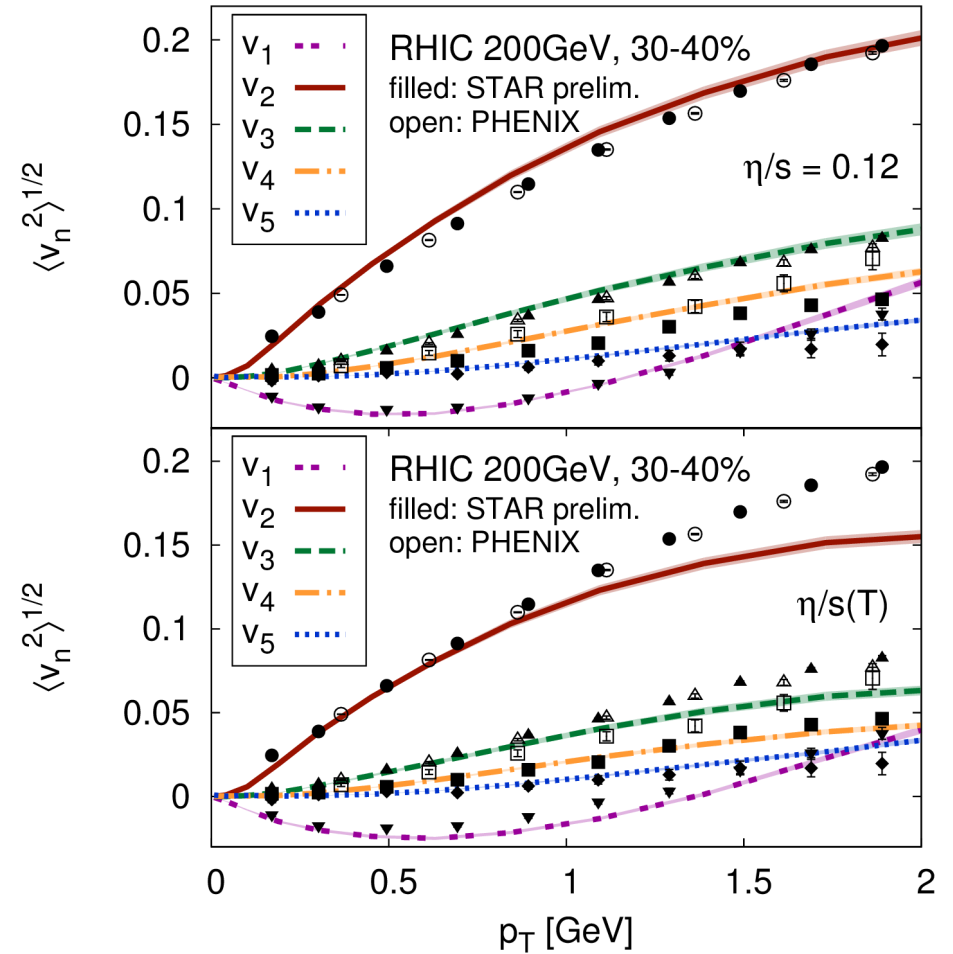
MC-KLN



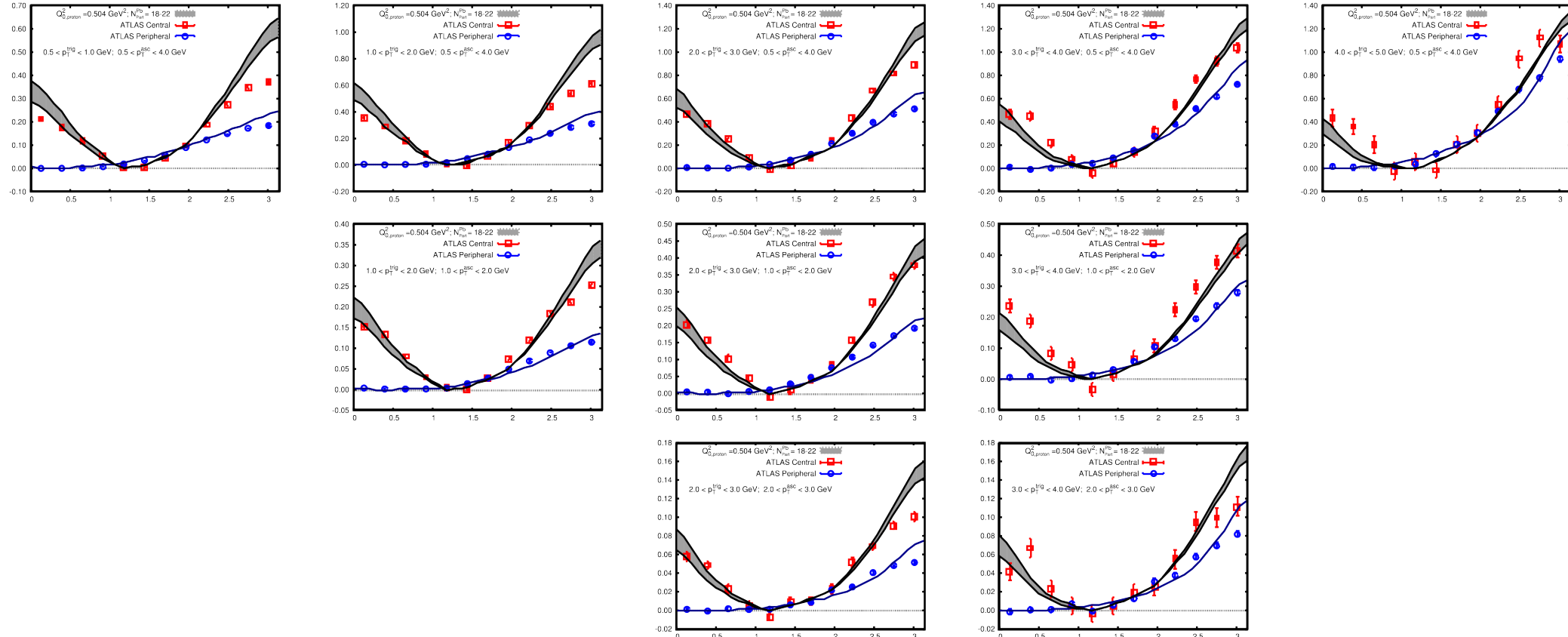
MC-Glauber



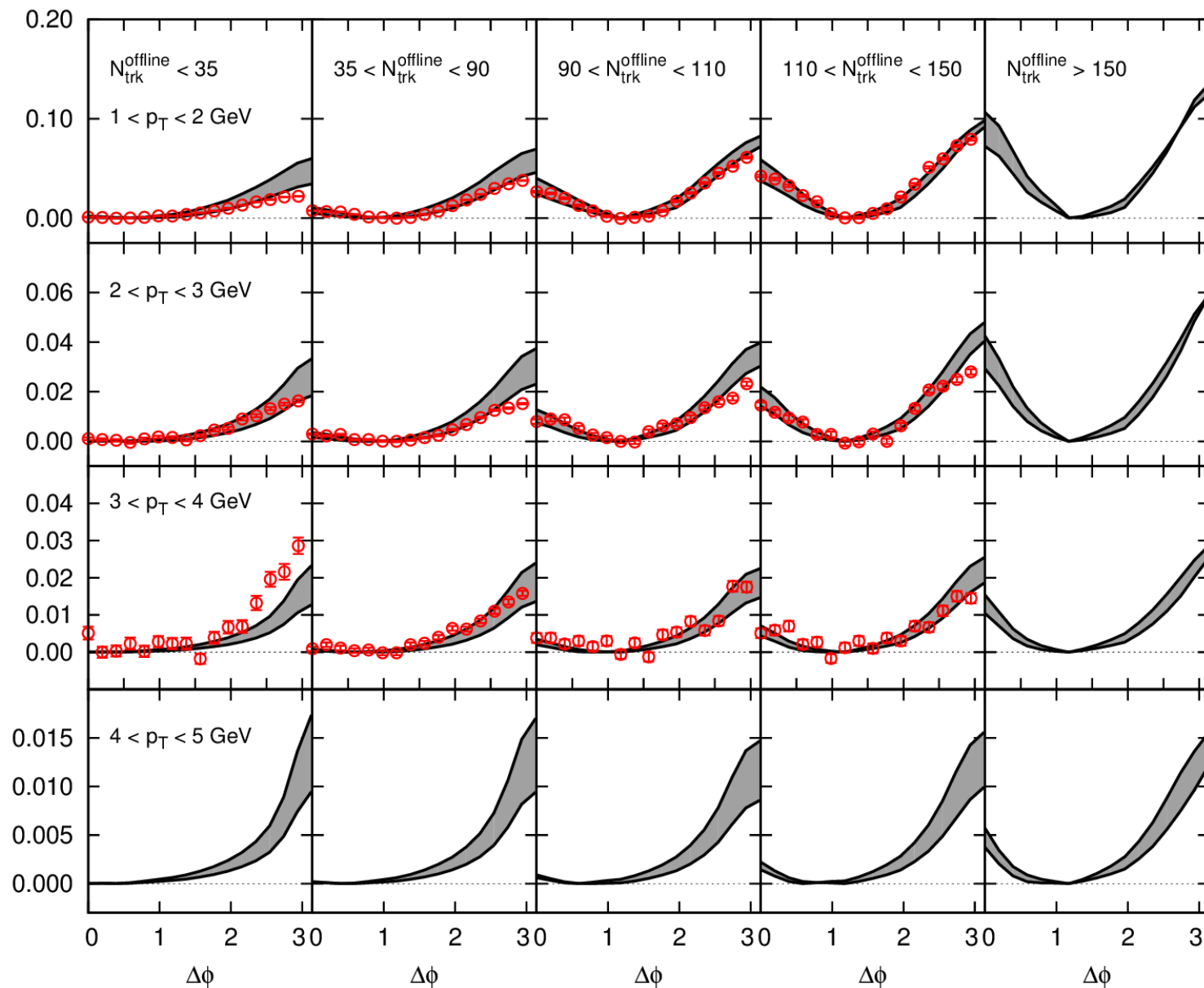
Gale, Jeon, Schenke, Tribedy, Venugopalan, arXiv:1209.6330



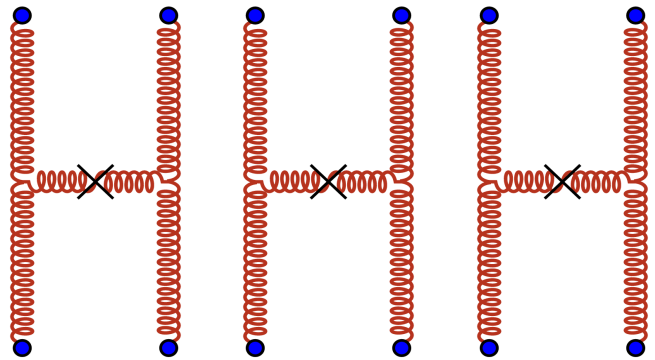
ATLAS Systematics



CMS Systematics



High multiplicity are b=0 collisions



$$P_n^{\text{NB}}(\bar{n}, k) = \frac{\Gamma(k+n)}{\Gamma(k)\Gamma(n+1)} \frac{\bar{n}^n k^k}{(\bar{n}+k)^{n+k}}$$

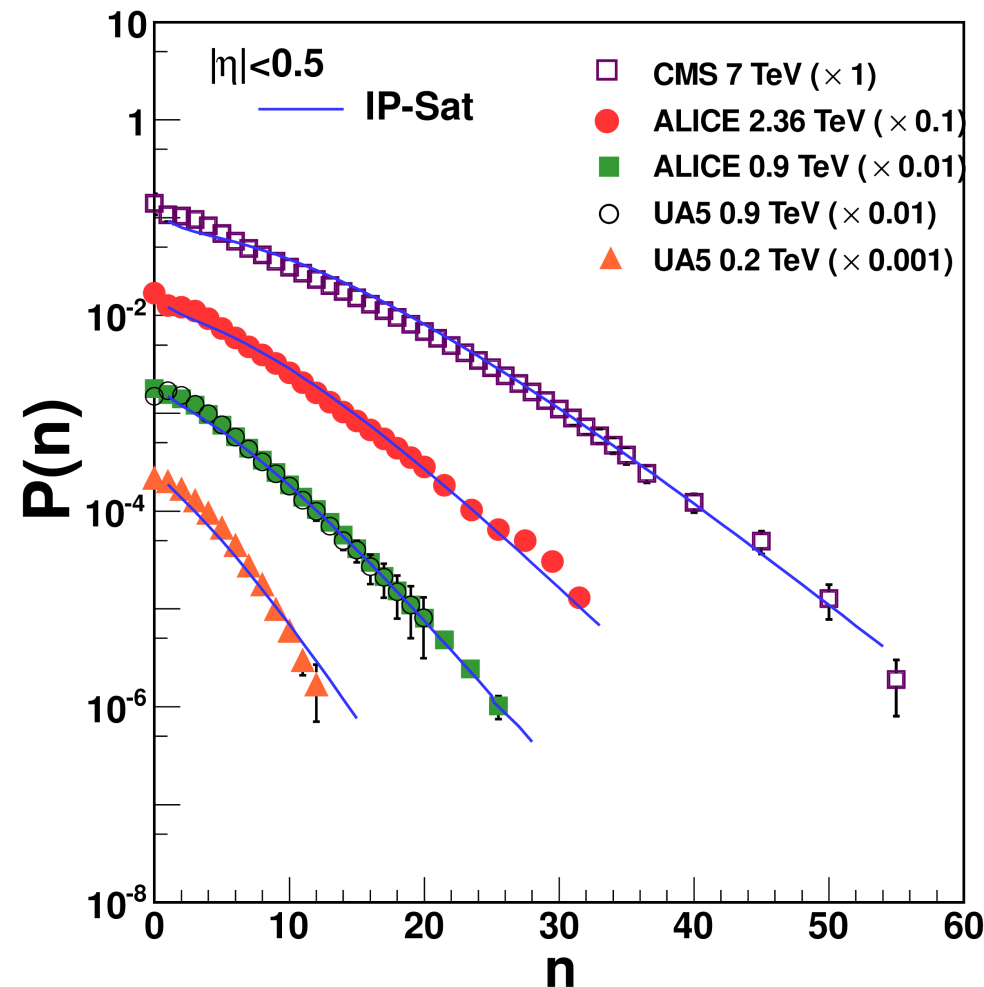
Dumitru, Gelis, McLerran, Venugopalan, NPA810 91-108 (2008).
 Dusling, Fernandez-Fraile, Venugopalan NPA828 (2009) 161-177.
 Gelis, Lappi, McLerran, NPA828 (2009) 149-160.

$$k = \zeta \frac{(N_c^2 - 1) S_{\perp} Q_s^2}{2\pi}$$

$$\zeta = 0.155 \text{ [Empirical]}$$

$$\zeta = 0.2 - 1.5 \text{ [Lattice]}$$

Empirical: Tribedy, Venugopalan, NPA850 (2011) 136-156.
 Lattice (CYM): Lappi, Srednyak, Venugopalan, JHEP01 (2010) 066.
 Schenke, Tribedy, Venugopalan, arXiv:1206.6805



Predictions for p+Pb

